Analysis of sediment sulfide concentration data from Environmental Management Program Tier 2 monitoring at salmon farms in southwestern New Brunswick, 2007-2011

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ABSTRACT

Chang, B.D., Bennett, A.T., Lyons, T.A., Parker, E.V., and Page, F.H. 2013. Analysis of sediment sulfide concentration data from Environmental Management Program Tier 2 monitoring at salmon farms in southwestern New Brunswick, 2007-2011. Can. Tech. Rep. Fish. Aquat. Sci. 3033: v + 49 p.

The New Brunswick Environmental Management Program requires annual Tier 1 monitoring at all approved fish farms. Tier 1 monitoring is conducted under the edges of 2-8 cages located along the perimeter of the cage array, with priority given to higher biomass cages. Sediment samples from monitoring stations are analyzed for total dissolved sulfides and oxidation-reduction (redox) potential. Spatially intensive Tier 2 monitoring is required at farms which receive poor ratings (Hypoxic B or worse), based on the mean sulfide concentration in Tier 1 monitoring. Tier 2 monitoring requires many more sampling stations, including under the outer edges of all perimeter cages and between all cages in the array. This study compared Tier 1 and Tier 2 sulfide results for the 14 Tier 2 monitoring events conducted during 2007-2011. For both Tiers, there were wide variations in sulfide concentrations among stations within each site, and often among the triplicate samples taken at individual stations. Tier 1 results were significantly higher than Tier 2 results in 11 of the 14 cases. In most Tier 2 monitoring events, there were no significant differences in the sulfide concentration between "cage edge" and "between cage" stations. Mean sulfide concentrations in Tier 2 monitoring increased with increasing total biomass on site, but with high variability, and some farms holding no fish had high sulfide concentrations. However, there were no clear relationships between the biomass per cage and sediment conditions in the vicinity of each cage. The area of seafloor with elevated sulfide concentrations (estimated from contour plots) in Tier 2 monitoring also increased in size with increasing total biomass on site, but with high variability (but less variability than the relationship between the mean sulfide concentration and biomass). In three of the Tier 2 monitoring events, more than two-thirds of the total seafloor area (under the cage array) had elevated impacts, while in the other 11 Tier 2 events, the area with elevated impacts covered 0-38% of the total area. There was a negative relationship between the sediment sulfide concentration and the redox potential in the Tier 2 monitoring data, but with high variability, as has been reported in previous studies.

RÉSUMÉ

Chang, B.D., Bennett, A.T., Lyons, T.A., Parker, E.V., and Page, F.H. 2013. Analysis of sediment sulfide concentration data from Environmental Management Program Tier 2 monitoring at salmon farms in southwestern New Brunswick, 2007-2011. Can. Tech. Rep. Fish. Aquat. Sci. 3033: v + 49 p.

Le New Brunswick Environmental Management Program (Programme de gestion environnementale au Nouveau-Brunswick) exige une surveillance annuelle de niveau 1 dans toutes les exploitations piscicoles approuvées. La surveillance de niveau 1 est effectuée sous le bord de 2 à 8 cages situées sur le périmètre de l'ensemble des cages, en accordant la priorité aux cages ayant la biomasse la plus élevée. Les échantillons de sédiments des stations de surveillance seront analysés afin d'y déceler les sulfures totaux dissous et le potentiel d'oxydoréduction (redox). La surveillance de niveau 2 spatialement intensive est exigée dans les exploitations recevant de mauvaises notations (hypoxique B ou pire), en fonction de la concentration moyenne de sulfures durant la surveillance de niveau 1. La surveillance de niveau 2 exige encore plus de stations d'échantillonnage, notamment sous les bords extérieurs de toutes les cages situées sur le périmètre ainsi qu'entre toutes les cages de l'ensemble. Cette étude a fait la comparaison des résultats de sulfures pour la surveillance de niveau 1 et de niveau 2 pour les 14 surveillances de niveau 2 effectuées de 2007 à 2011. Pour les 2 niveaux, il y avait un écart important dans les concentrations de sulfures parmi les stations de chaque site, et souvent dans les trois sous-échantillons prélevés aux stations individuelles. Les résultats du niveau 1 étaient beaucoup plus élevés que ceux du niveau 2 pour 11 des 14 surveillances. Dans la plupart des surveillances de niveau 2, aucune différence importante n'a été décelée entre la concentration de sulfures pour les stations situées au bord des cages et celles situées entre les cages. Les concentrations moyennes de sulfures pour la surveillance de niveau 2 ont augmenté avec l'augmentation de la biomasse totale sur le site, mais elles avaient une grande variabilité. De plus, certaines exploitations n'ayant pas de poisson avaient des concentrations de sulfures élevées. Cependant, il n'y avait aucun lien clair entre la biomasse par cage et la condition des sédiments à proximité de chaque cage. La zone du plancher océanique ayant des concentrations de sulfures élevées (estimées à partir des tracés de contours) durant la surveillance de niveau 2 a également augmenté avec l'augmentation de la biomasse totale sur le site, mais elle avait une grande variabilité (toutefois, elle était moins variable que le lien entre la concentration moyenne de sulfures et la biomasse). Dans 3 des surveillances de niveau 2, plus de deux tiers de la zone totale du plancher océanique (sous l'ensemble des cages) avait des répercussions élevées, tandis que durant les autres 11 surveillances de niveau 2, la zone ayant des répercussions élevées couvrait de 0 à 38 % de la zone totale. Il y avait une relation négative entre la concentration de sulfures des sédiments et le potentiel de redox dans les données de surveillance de niveau 2, mais elles avaient une grande variabilité, comme le signalaient des études précédentes.

INTRODUCTION

Marine finfish cage aquaculture in New Brunswick is conducted in the southwestern region (SWNB), in the Bay of Fundy. At present, almost all finfish aquaculture production in this area is Atlantic Salmon (*Salmo salar*). *The Environmental Management Program for the Marine Finfish Cage Aquaculture Industry in New Brunswick* requires annual Tier 1 monitoring at all farms that have approvals to operate, and more intensive Tier 2 monitoring at farms where Tier 1 results indicate that adverse environmental impacts are likely occurring (NBDELG 2012a). Tier 1 monitoring is conducted during August-October under the outer edges of selected cages located along the perimeter of the cage array (Fig. 1). Cage selection is based on fish biomass (the highest biomass cages are given priority), the cage array layout, water current patterns, and the direction of the shoreline (NBDELG 2012b). The number of cages monitored in Tier 1 monitoring is determined by the number of fish present: a minimum of two cages, plus an additional cage for every 100 000 fish (or part thereof) above 200 000 fish. During 2007-2009, Tier 1 monitoring was usually conducted by divers using core tubes (approximately 30 cm long and 5 cm in diameter). Surface-deployed grab samplers were used at the few farms where the water depth at the site centre was >30.5 m at mean low tide (NBDENV 2007). In 2010, surface-deployed grab samplers could be used for Tier 1 monitoring if the depth at any one sampling station was >30 m at low tide (NBDENV 2010). Since 2011, either diver-retrieved cores or surface-deployed grab samplers can be used, regardless of water depth (NBDELG 2012b). Triplicate samples are collected from the top 2 cm of sediment at each monitoring station and analyzed for total sulfide concentration: either one sample from each of 3 diver-retrieved cores taken within a 1 m^2 area at each station, or 3 samples from one surface-deployed grab sample at each station. The sulfide concentration (mean of all samples taken in Tier 1 monitoring) is used to rate each farm according to Table 1. The oxidation-reduction (redox) potential is also measured in each sample, but is not used to rate the farm, although it contributes to the overall site assessment.

When Tier 1 monitoring results in ratings of Hypoxic B or worse (mean sulfide concentration >3000 µM), Tier 2 monitoring must be conducted within 20 d (NBDELG 2012a). Tier 2 monitoring protocols implemented in 2007 require sampling at many more stations (Fig. 2), including four stations around the circumference of each corner cage, under the outer cage edge of all other perimeter cages, and between all cages within the cage array; however, there are no stations outside the cage array (NBDELG 2012b). Either diver-retrieved cores or surface-deployed grab samplers can be used for Tier 2 monitoring, regardless of water depth. As with the Tier 1 monitoring, triplicate samples are taken at each station for sulfide analysis (either one sample from each of 3 cores, or 3 samples from one grab), but only one redox measurement is required per station.

The purpose of this study was to examine the results from the 14 Tier 2 monitoring events conducted at SWNB salmon farms during 2007-2011. The following questions were addressed:

1) How do Tier 2 sulfide concentration results compare to Tier 1 results? For farms where Tier 2 monitoring has been conducted, should the Tier 2 results be used to determine the farm's environmental rating?

2) In the Tier 2 data, how do sulfide concentrations in samples taken at cage edges compare to concentrations in samples taken between cages?

3) What is the spatial extent of elevated benthic impacts, as determined by Tier 2 monitoring of sulfide concentrations?

4) What is the relationship between sediment sulfide concentrations and redox potential values in Tier 2 monitoring?

METHODS

Tier 2 monitoring reports were provided by the New Brunswick Department of Environment and Local Government (NBDELG). Details on sampling and geochemical analytical methods can be found in NBDELG (2012b). During 2007-2011 there were 14 Tier 2 monitoring events conducted, at 11 different farms (Table 2): 9 farms conducted Tier 2 monitoring once, one farm conducted Tier 2 monitoring twice, and one farm conducted Tier 2 monitoring three times. Tier 1 data from the same years at these farms were also provided by NBDELG. There were a few sampling points where the station coordinates in the monitoring reports were found to be incorrect when plotted (i.e. they did not match the locations indicated on site plans or aerial photos); in such cases, the station coordinates were adjusted. Approximate cage locations were determined from site plans, aerial photos, and/or the locations of monitoring stations. Data on the fish biomass per cage at the time of monitoring were obtained from monitoring reports or from farm operators; such data were not available for all monitoring events.

For the 14 Tier 2 monitoring events included in this study, diver-retrieved cores were used in all cases during 2007-2009 and surface-deployed grab samplers were used in all cases in 2010-2011. The corresponding Tier 1 monitoring was conducted using diver-retrieved cores in all but 3 cases: for MF-251 (2010 and 2011) and MF-342 (2011), surface-deployed grab samplers were used. Further details on the monitoring methods are provided in the Introduction.

Comparisons were made between sulfide concentrations in Tier 1 vs. Tier 2 monitoring. Any differences could be due to temporal and/or spatial factors. To determine the importance of temporal factors alone, comparisons were made between Tier 1 data vs. the subset of Tier 2 data collected at Tier 1 stations (i.e. both sets of samples taken at approximately the same locations, but on different dates). To determine the importance of spatial factors alone, comparisons were made between the subset of Tier 2 data collected at Tier 1 stations vs. all other Tier 2 stations (i.e. both sets of data taken on the same date, but at different locations).

Comparisons were also made between sulfide concentrations at all "cage edge" stations vs. all "between cage" stations (see Fig. 2). Where there were "cage edge" and adjacent "between cage" stations in close proximity, paired comparisons were made; this was possible for the two inner "cage edge" stations at each corner cage (i.e. 8 pairs at most farms; see Fig. 2).

Statistical comparisons were made using non-parametric tests, because most Tier 2 monitoring sulfide concentration datasets deviated from normality and because of the small sample sizes (especially for Tier 1 data). Most comparisons were made on individual sample data (triplicate samples at each station) using the Mann-Whitney U test. For comparisons of paired samples at "cage edge" and adjacent "between cage" stations, the Wilcoxin paired sample signed-rank test was used to compare means for the station pairs at each farm. All tests were 2-tailed, with α=0.05. Tests were performed using the University of California Statistics Online Computational Resource (http://www.socr.ucla.edu/SOCR.html).

Contour plots of the Tier 2 sulfide concentration data were created using MapInfo Professional (version 8.0) and MapInfo Vertical Mapper (version 3.0). The interpolation technique was Natural Neighbor (simple); this technique appeared to be a reasonable choice for the distributions of sediment sampling points, based on recommendations in this software. Default values (calculated by the contouring software) were used for Cell Size and Aggregation Distance. The Surface Solution Type used was Smoothed, without overshoot (the default choice). Contour intervals were taken from Table 1. Calculations of the seafloor areas within the contour intervals assumed a flat bathymetry.

The relationship between the sediment sulfide concentration ($\mu M\ S^{2-}$) and the oxidation-reduction (redox) potential (mV_{NHE}, millivolts relative to the normal hydrogen electrode) was examined. The Tier 2 protocols require 3 sulfide measurements per station, but only one redox measurement per station. For the sulfide-redox relationships, the mean sulfide concentration per station was plotted against the one redox measurement per station, except at the farms monitored in 2008, when 3 redox measurements were taken per station; in these cases, the mean redox values per station were used.

RESULTS

TIER 1 AND TIER 2 SULFIDE CONCENTRATIONS

Mean sulfide concentrations for Tier 2 monitoring during 2007-2011, together with corresponding Tier 1 monitoring results, are shown in Table 3 and Fig. 3. There were wide variations in sulfide concentrations among samples within each monitoring event, as shown by the large standard deviations (Fig. 3). There were also wide variations in the sulfide concentrations among triplicate samples taken at some of the monitoring stations, as indicated by some large standard deviations and coefficients of variation (Table 4). In most cases, the mean standard deviations and mean coefficients of variation in Tier 2 monitoring events were lower than in the corresponding Tier 1 monitoring events (Table 4).

There were significant differences in Tier 1 vs. Tier 2 results in 11 of the 14 cases; the exceptions were MF-053 in 2011, MF-215 in 2011, and MF-342 in 2011 (Table 5). The mean sulfide concentration in Tier 2 monitoring was lower than the mean in Tier 1 monitoring in all of the 11 cases with significant differences. The time interval between the dates of Tier 1 and Tier 2 monitoring ranged from 4-29 d (mean = 17 d).

Comparisons of the Tier 1 sulfide concentrations vs. concentrations at corresponding stations in the Tier 2 monitoring (i.e. similar sample locations, but different sampling times) indicated significant differences in 5 of the 14 cases (Table 6). In all 5 cases where significant differences were found, the Tier 1 sulfide concentrations were higher. There was no apparent effect of the length of the time interval between the dates of the two tiers of monitoring: the average interval was 17 d, both for the cases showing significant differences and those showing no significant differences.

Comparisons of the sulfide concentrations in the subset of Tier 2 samples taken at Tier 1 stations vs. the concentrations at all other Tier 2 stations (i.e. same sampling times, but different sample locations) indicated significant differences in 6 of the 14 Tier 2 monitoring events (Table 7). In 5 of the 6 events where significant differences were found, the higher sulfide concentrations were at the Tier 1 stations; the exception was MF-251 in 2011.

Of the 11 cases where there were significant differences in the sediment sulfide concentration in Tier 1 vs. Tier 2 results, temporal factors alone were significant in 2 cases (MF-010 in 2007 and MF-251 in 2010); spatial factors alone were significant in 3 cases (MF-037 in 2008, MF-502 in 2008, and MF-342 in 2010); both temporal and spatial factors were significant in 3 cases (MF-342 in 2007, MF-026 in 2009, and MF-251 in 2011); and neither temporal nor spatial factors alone were significant in 3 cases (MF-061 in 2007, MF-002 in 2008, and MF-186 in 2008; see Table 8).

SULFIDE CONCENTRATIONS AT "CAGE EDGE" VS. "BETWEEN CAGE" STATIONS

Comparisons of sulfide concentrations at all "cage edge" stations vs. concentrations at all "between cage" stations indicated no significant differences in 9 of the 14 Tier 2 monitoring events (Table 9). In the 5 events where there were significant differences, the higher concentrations were at the cage edge stations.

In paired comparisons of mean sulfide concentrations at "cage edge" stations vs. adjacent "between cage" stations (i.e. the two inner "cage edge" samples at each corner cage compared with the adjacent "between cage" samples), there were no significant differences in 11 of 13 Tier 2 monitoring events (Table 10). In the 2 events where significant differences were found, the sulfide concentration was higher in the "cage edge" stations. For one Tier 2 monitoring event there was an insufficient number of data points to allow paired comparisons (MF-186 in 2008).

RELATIONSHIP BETWEEN FARM BIOMASS AND MEAN SULFIDE CONCENTRATION

Farm biomass data were available for 11 of the 14 Tier 2 monitoring events and for 11 of the 14 corresponding Tier 1 monitoring events (Table 2). The Tier 1 mean sulfide concentration showed a general increase as fish biomass increased (Fig. 4), but with a low r^2 value (0.21). Sulfide concentrations were elevated (Hypoxic B) at the 4 farms holding no fish at the time of Tier 1 monitoring. In one of these cases (MF-251 in 2011) the farm had been fallow for one week; in

two cases (MF-502 in 2008 and MF-053 in 2011) the farms had been fallow about one month; and in the third case (MF-342 in 2011) the farm had been fallow about 3 months.

The Tier 2 mean sulfide concentration also showed a general increase as fish biomass increased (Fig. 4), but with a very low r^2 value (0.10). There were 4 Tier 2 monitoring events at farms holding no fish; these were the same cases where there was Tier 1 monitoring at farms holding no fish. Of these 4 cases, the Tier 2 rating was worse (Hypoxic C) than the Tier 1 rating in one case (MF-342 in 2011) and better (Oxic B or Hypoxic A) in the other 3 cases. Tier 2 sulfide concentrations were usually lower than Tier 1 concentrations for similar biomasses (Fig. 5).

CONTOUR PLOTS OF TIER 2 SULFIDE CONCENTRATIONS

Contour plots of the Tier 2 monitoring results are shown in Fig. 6 to 19. Calculated seafloor areas within the contour intervals at each site are shown in Table 11.

MF-010 (2007): The mean sulfide concentration per monitoring station ranged from 98-5 023 µM. The total contoured area (Fig. 6) was mostly oxic (71%). Only 6% of the contoured area had Hypoxic B or worse conditions and there were no anoxic areas. The elevated impacts were mostly in the western half of the site. The fish biomass was not evenly distributed among the 34 cages: 5 cages were empty, and each of the other 29 cages held 6 500-26 900 kg (1.5-6.4% of the total biomass) at the time of the Tier 2 monitoring. Benthic impact was not related to cage biomass: the highest sulfide concentrations occurred under a cage holding a relatively low biomass, and sulfide concentrations were at background levels under the cage holding the highest biomass.

MF-061 (2007): The mean sulfide concentration per monitoring station ranged from 519-6 837 µM. Of the total contoured area (Fig. 7), 38% had Hypoxic B or worse conditions, including a very small anoxic area (1%). No data were available on the distribution of the fish biomass among the 23 cages.

MF-342 (2007): The mean sulfide concentration per monitoring station ranged from 292-5 857 µM. The total contoured area (Fig. 8) was mostly oxic (72%). Only 10% of the contoured area had Hypoxic B or worse conditions (confined to the western edge of the site) and there were no anoxic areas. The Tier 1 monitoring report indicated that there were 192 000 fish on site, with the biomass evenly distributed among the 12 cages (8.3% per cage).

MF-002 (2008): The mean sulfide concentration per monitoring station ranged from 177-7 918 µM. Of the total contoured area (Fig. 9), 19% had Hypoxic B or worse conditions, including a small anoxic area (5%). The most highly impacted sediments were under the northernmost row of cages, in the shallowest part of the site, plus a small impacted area under the southeastern corner cage. The Tier 2 monitoring report indicated that the biomass was evenly spread among the 20 cages.

MF-037 (2008): The mean sulfide concentration per monitoring station ranged from 108-6 537 µM. Of the total contoured area (Fig. 10), 31% had Hypoxic B or worse conditions,

including a very small anoxic area (1%). The most highly impacted areas were at the northwest and southwest corners. The fish biomass was not evenly distributed among the 16 cages: individual cages held 16 300-76 000 kg (2.6-12.3% of the total biomass) at the time of the Tier 2 monitoring. Benthic impact was not related to cage biomass: the highest sulfide concentrations occurred under the cage with the second lowest biomass (at the northwestern corner), and the lowest sulfide concentrations occurred under the cage with the highest biomass (at the southwestern corner).

MF-186 (2008): The mean sulfide concentration per monitoring station ranged from 25-2 160 µM. The contour plot for this site (Fig. 11) is based on very few sampling points (15). The total contoured area was mostly oxic (89%), and there were no areas with Hypoxic B or worse conditions. The Tier 1 monitoring report indicated that there were 140 000 fish on site, with the biomass evenly distributed among the 4 cages (25% per cage).

MF-502 (2008): The mean sulfide concentration per monitoring station ranged from 17-5 543 µM. The total contoured area (Fig. 12) was mostly oxic (78%). Only 13% of the contoured area had Hypoxic B or worse conditions and there were no anoxic areas. The most highly impacted areas were in the northeastern portion of the site. There were no fish in the 10 cages on site at the time of monitoring; harvesting had been completed 1-2 months prior to Tier 2 monitoring.

MF-026 (2009): The mean sulfide concentration per monitoring station ranged from 1 050-8 703 µM. Most of the total contoured area (Fig. 13) had Hypoxic B or worse conditions (89%), including a substantial area with anoxic sediments (24%). The fish biomass was relatively evenly distributed among the 33 cages, with each cage holding 44 300-63 700 kg (2.5-3.6% of the total biomass) at the time of Tier 2 monitoring.

MF-251 (2010): The mean sulfide concentration per monitoring station ranged from 321-9 777 µM. Of the total contoured area (Fig. 14), 13% had Hypoxic B or worse conditions, including a small anoxic area (3%). The fish biomass was not evenly distributed among the 12 cages: individual cages held 31 800-109 100 kg (3.1-10.6% of the total biomass) at the time of the Tier 2 monitoring. The most highly impacted areas (at the western and southeastern areas of the site), were not under the cages holding the highest biomasses.

MF-342 (2010): The mean sulfide concentration per monitoring station ranged from 803-8 597 µM. Almost two-thirds of the total contoured area (Fig. 15) had Hypoxic B or worse conditions (63%), including substantial anoxic areas (13%). On 28 August 2010 (midway between the Tier 1 and Tier 2 monitoring dates), the fish biomass was relatively evenly distributed among 14 of the 15 cages, with each holding 34 700-47 100 kg (6.0-8.2% of the total biomass); the remaining cage (the second cage from the north in the middle column) held fewer fish, 11 900 kg, or 2.1% of the total biomass.

MF-053 (2011): The mean sulfide concentration per monitoring station ranged from 728-5 177 µM. The total contoured area (Fig. 16) was mostly oxic (53%). Only 3% of the contoured area had Hypoxic B or worse conditions, and there were no anoxic areas. There were no fish in

the 13 cages on site at the time of Tier 1 and Tier 2 monitoring; harvesting had been completed about one month prior to the Tier 1 monitoring.

MF-215 (2011): The mean sulfide concentration per monitoring station ranged from 90-16 000 µM. About one-third of the total contoured area (Fig. 17) had Hypoxic B or worse conditions (31%), including 14% with anoxic sediments. The most highly impacted areas were in the northern and eastern parts of the site (the shallower areas). At the time of the Tier 1 monitoring (14 October 2011), the fish biomass was relatively evenly distributed among 16 cages (there was also one empty cage), with each cage holding 84 800-133 800 kg (4.5-7.1% of the total biomass); harvesting started on the day of Tier 1 monitoring, and approximately 13% of the salmon biomass had been harvested by the day of Tier 2 monitoring (18 October 2011).

MF-251 (2011): The mean sulfide concentration per monitoring station ranged from 38-11 330 µM. The total contoured area (Fig. 18) was mostly oxic (84%). Only 16% of the contoured area had Hypoxic B or worse conditions, including a small anoxic area (2%). There were no fish in the 12 cages on site at the time of Tier 2 monitoring; harvesting had been completed just before the Tier 1 monitoring (early October 2011).

MF-342 (2011): The mean sulfide concentration per monitoring station ranged from 1 108-15 000 µM. Most of the total contoured area (Fig. 19) had Hypoxic B or worse conditions (83%), including a large anoxic area (38%). There were no fish in the 15 cages on site at the time of Tier 1 and Tier 2 monitoring; harvesting had been completed 3-4 months prior to Tier 2 monitoring.

RELATIONSHIP BETWEEN FARM BIOMASS AND THE CONTOUR AREA WITH ELEVATED SULFIDE CONCENTRATION

The seafloor area with elevated sulfide concentrations showed a general increase as fish biomass increased (Fig. 20). For the relationship between biomass and the area with sulfide concentrations equivalent to Hypoxic B or higher (>3 000 µM), $r^2 = 0.36$. For the relationship between biomass and the area with sulfide concentrations equivalent to Hypoxic A or higher (>1 500 µM), $r^2 = 0.46$.

One farm holding no fish (MF-342 in 2011) had elevated sulfide concentrations (i.e. greater than Hypoxic A or B) in most of the total contoured area (>80%); this farm had been fallow for about 3 months. In the other 3 cases where there were no fish at the time of Tier 2 monitoring, <25% of the total contoured area had elevated sulfide concentrations.

RELATIONSHIP BETWEEN SEDIMENT SULFIDE CONCENTRATION AND OXIDATION-REDUCTION (REDOX) POTENTIAL

Graphs of the relationship between the sediment sulfide concentration (log-transformed) and the oxidation-reduction (redox) potential in each Tier 2 monitoring event are shown in Fig. 21. There were negative relationships between the sulfide concentration and the redox potential in all cases, but often with high variability: r^2 values for the linear relationship between the sulfide

concentration (log-transformed) vs. the redox potential in individual Tier 2 monitoring events ranged from 0.17-0.88. Redox values for several stations at MF-186 (2008) were lower (for equivalent sulfide concentrations) than at other sites. The graph of the sulfide concentration (log-transformed) vs. the redox potential for all Tier 2 data combined indicated a non-linear relationship (Fig. 21); the r^2 value for a linear relationship was 0.39.

DISCUSSION

COMPARISON OF SULFIDE CONCENTRATIONS IN TIER 1 AND TIER 2 MONITORING

The mean sulfide concentration in Tier 2 monitoring was significantly lower than the mean concentration in Tier 1 monitoring in 11 of the 14 cases. Environmental ratings based on Tier 2 monitoring would be better than ratings based on Tier 1 monitoring in 12 of the 14 cases, worse in one case, and no change in the other case (see Table 3).

Comparisons of Tier 1 monitoring results with those from corresponding stations in Tier 2 monitoring (i.e. approximately the same sample locations, but different dates) found no significant differences in 9 of the 14 cases. This suggests that, at least for these 9 cases, the temporal differences between the two tiers of monitoring did not have a significant effect on the sulfide concentrations (at least at the Tier 1 monitoring stations). Tier 2 monitoring should be conducted within 20 d of Tier 1 monitoring (NBDELG 2012b). The 14 Tier 2 monitoring events in this study occurred, on average, within 17 d of the Tier 1 monitoring. This short time interval between Tier 1 and Tier 2 monitoring would suggest that temporal factors should not be important in explaining the differences between Tier 1 and Tier 2 results. However, there were significant differences in the other 5 cases, suggesting that temporal factors may have been important in these cases, although it is possible that small-scale spatial factors were important (see below). The length of the time interval between the two tiers averaged the same (17 d) in the cases where significant differences in mean sulfide concentrations were found and in the cases where there were no significant differences. In another study in SWNB, large differences in sulfide concentrations were sometimes observed between samples taken at 1-2 week intervals at two salmon farms (Page et al. 2011), suggesting that temporal factors can sometimes be important, even over relatively short time intervals. Temporal differences in sediment sulfide concentrations may sometimes be due to operational changes at the farms between dates of the two tiers of monitoring, such as decreases in biomass due to harvesting, movements of fish among cages, and/or decreases in feeding that may have been implemented in response to poor Tier 1 results. There may also have been changes in physical environmental conditions between Tier 1 and Tier 2 monitoring dates, such as due to storm events.

Where differences were found between Tier 1 monitoring results and corresponding stations in Tier 2 monitoring, small-scale spatial differences may also have been important, since the corresponding Tier 2 stations were not in exactly the same locations as the Tier 1 stations, due to cage movement (all of these samples were taken at cage edges). Other studies have determined that fish cages in SWNB can move horizontally in the order of 10-40 m over a tidal cycle (S. Smedbol, unpublished data; Hanke 2010), so a "cage edge" sample taken at one time will not

likely be in exactly the same location as a sample taken at the edge of the same cage at another time. The wide variation in sulfide concentrations among triplicate samples observed at some Tier 1 and Tier 2 stations indicates that small-scale spatial variation can occur (i.e. within a 1 m^2 area). In another study in SWNB, wide variations were sometimes observed among triplicate samples taken from small (0.024-0.096 m^2) grab samples (Chang et al. 2011). The generally smaller standard deviations and coefficients of variation in Tier 2 monitoring (compared to Tier 1) were likely mainly due to the much larger number of samples in Tier 2 monitoring.

Comparisons of Tier 2 monitoring results from Tier 1 stations vs. all other stations (i.e. the same sampling dates, but different locations) indicated significant differences in 6 of the 14 Tier 2 monitoring events, with the higher concentrations at the Tier 1 stations in all but one of these 6 cases. Higher Tier 1 values would not be unexpected, since Tier 1 monitoring targets higher biomass cages (along the perimeter of the cage array), while Tier 2 monitoring is more representative of an overall average under the cage array. However, at the other 8 Tier 2 monitoring events, no significant differences were found, suggesting that, at least in these cases, the mean sulfide concentration at Tier 1 monitoring stations was representative of the mean under the cage array.

COMPARISON OF SULFIDE CONCENTRATIONS AT "CAGE EDGE" VS. "BETWEEN CAGE" STATIONS

There were no significant differences between sulfide concentrations in samples taken at "cage edges" compared to samples taken "between cages" in the majority of cases. Comparisons involving all "cage edge" and all "between cage" stations found no significant differences in 9 of the 14 Tier 2 monitoring events. In the 5 cases where significant differences were found, all had higher concentrations at the cage edges. When comparing paired samples of "cage edge" stations and adjacent "between cage" stations, no significant differences were found in 11 of 13 Tier 2 monitoring events. Therefore, it does not appear that taking only "between cage" samples within the cage array (versus "cage edge" samples along the perimeter and at corner cages) has any consistent effect on the Tier 2 monitoring results at salmon farms in SWNB.

It might be expected that sediments taken at "cage edge" stations would have higher sulfide concentrations compared to "between cage" stations, since wastes generally fall directly under cages, except where currents are strong. One possible reason for not finding a significant difference in most Tier 2 monitoring events is cage movement during the tidal cycle (see above); hence, the location where a "cage edge" sample is taken may be situated between cages at some stages of the tide, and similarly, a "between cage" station may be situated under a cage at some stages of the tide. At farms where there is less cage movement, such as in locations where tides are smaller than in SWNB, there may be greater differences in sulfide concentrations between "cage edge" and "between cage" sampling stations.

RELATIONSHIP BETWEEN FARM BIOMASS AND MEAN SEDIMENT SULFIDE CONCENTRATION

There was a general trend of increasing mean sediment sulfide concentration with increasing fish biomass for both Tier 1 and Tier 2 monitoring, but the relationships had considerable variation (r^2 values were very low). Tier 1 results were mostly higher than Tier 2 results at the same biomass. One farm with no fish on site at the time of Tier 2 monitoring (MF-342 in 2011) had a high mean sulfide concentration (Hypoxic C). The high sulfide concentration at this farm was likely due to residual effects of fish held at this farm earlier in the year, although the farm had been fallow for about 3 months at the time of monitoring. This farm also had high sulfide concentrations in the previous year (2010), as well as in 2007. This farm was located in an area with very low current speeds; this may be a reason for the slow recovery of the benthic environment under this farm after harvesting. In another case, slightly elevated sulfide concentrations (Hypoxic A) were found at MF-053 in 2011 when no fish were on site; this farm had been fallow for about 1 month at the time of Tier 2 monitoring and was also in an area with low current speeds. In the other two cases where farms were fallow at the time of Tier 2 monitoring, sulfide concentrations were lower (Oxic B); each of these farms had been fallow for about 1 month.

SPATIAL EXTENT OF IMPACTED SEAFLOOR AREAS (BASED ON CONTOUR PLOTS OF TIER 2 MONITORING RESULTS)

Of the 14 Tier 2 monitoring events, elevated benthic conditions (Hypoxic B or worse; sulfide concentration >3000 µM) were found in more than two-thirds of the total contoured area in 3 cases: MF-026 (2009) and MF-342 (2010 and 2011). In the other Tier 2 monitoring events, the areas with elevated impacts comprised 0-38% of the total contoured area.

In the Tier 2 monitoring events for which information was available on the relative distribution of the fish biomass among cages at the time of monitoring, there were no consistent relationships between the biomass per cage and the intensity of benthic impacts in the vicinity of each cage. At MF-026 (2009) and MF-342 (2010) the biomass was relatively evenly distributed among the cages, and elevated impacts were found under most of the cage array. At MF-186 (2008), the biomass was reported to be evenly distributed among the cages, and impacts were relatively low throughout. However, at MF-342 (2007), MF-002 (2008), and MF-215 (2011), the fish biomass was also relatively evenly distributed among the cages, but the high impact areas were confined to small areas within the cage arrays; for MF-002 (2008) and MF-215 (2011), the higher impact areas were in shallower portions of these sites. At MF-010 (2007), MF-037 (2008), and MF-051 (2010) there were quite wide variations in the biomass per cage, but the spatial distribution of higher benthic impacts did not show good correspondence with the biomass per cage data. These observations describe the relationship between benthic impacts near each cage and the biomass per cage at the time of monitoring. If the relative biomasses among cages at a farm had changed substantially during the period prior to monitoring (due to transfers of fish among cages or harvesting), this may have had an effect on the relationship (or lack thereof) between the biomass per cage (at the time of monitoring) and the benthic impacts in the vicinity of each cage.

RELATIONSHIP BETWEEN FARM BIOMASS AND THE SEAFLOOR AREA WITH ELEVATED SULFIDE CONCENTRATION

There was a trend of increasing area of impacted seafloor (the surface area with elevated sulfide concentration in Tier 2 monitoring) as fish biomass increased. The relationships had considerable variability, but were stronger than the relationship between mean sulfide concentration (in Tier 2 monitoring) and fish biomass.

RELATIONSHIP BETWEEN SEDIMENT SULFIDE CONCENTRATION AND OXIDATION-REDUCTION POTENTIAL

There were negative relationships between the sulfide concentration and redox potential in all Tier 2 monitoring events, as has been reported in other studies at SWNB salmon farms (see Hargrave 2010). However, the linear regression of the sulfide concentration (log-transformed) and the redox potential for all Tier 2 data combined showed a poor fit ($r^2 = 0.39$) compared to other studies in SWNB (Table 12), and the redox values in the Tier 2 data appeared to be lower (for corresponding sulfide values) than in the other studies (Hargrave 2010; Wildish et al. 1999). The data appeared to best fit a non-linear exponential relationship similar to equation 1 in Hargrave (2010).

SUMMARY AND CONCLUSIONS

TIER 2 VS. TIER 1 SULFIDE CONCENTRATIONS:

- Mean sulfide concentrations in Tier 2 monitoring were significantly lower than the mean sulfide concentrations in Tier 1 monitoring in 11 of 14 cases.
- Environmental ratings based on Tier 2 monitoring would be better than ratings based on Tier 1 monitoring in 12 of the 14 cases.
- There was a wide range in sulfide concentrations among stations within each monitoring event.
- There were often wide variations in sulfide concentrations among the triplicate samples taken at each station.
- Both temporal (different dates of monitoring) and spatial (different locations of samples) factors may be important in causing the differences in sulfide concentrations between the two tiers of monitoring.

SULFIDE CONCENTRATIONS AT "CAGE EDGE" VS. "BETWEEN CAGE" STATIONS:

- Sulfide concentrations at "cage edge" stations were not significantly different from "between cage" stations in most Tier 2 monitoring events.

INFLUENCE OF FISH BIOMASS ON SULFIDE CONCENTRATION:

- Mean sulfide concentrations in Tier 2 (and Tier 1) monitoring increased with increasing fish biomass, but with very high variability. However, sulfide concentrations were elevated at some farms holding no fish, probably due to residual effects from fish previously held at these farms.
- In the Tier 2 monitoring events where fish biomass per cage data were available, there were no consistent relationships between the fish biomass in each cage and the benthic impacts in the vicinity of each cage.
- The contoured seafloor area with elevated sulfide concentrations in Tier 2 monitoring increased with increasing fish biomass, but with considerable variability (but less variability than in the relationship between mean sulfide concentration and fish biomass).

SPATIAL EXTENT OF IMPACTS BASED ON CONTOUR AREAS FOR TIER 2 SULFIDE CONCENTRATIONS:

- Of the 14 Tier 2 monitoring events during 2007-2011, there were three events where more than two-thirds of the contoured seafloor area had elevated impacts (Hypoxic B or worse). In the other 11 events, elevated areas were confined to patches covering from 0-38% of the total contoured area.

RELATIONSHIP BETWEEN SEDIMENT SULFIDE CONCENTRATION AND OXIDATION-REDUCTION POTENTIAL

- There was a negative relationship between the sediment sulfide concentration (log-transformed) and the redox potential, but with high variability. The relationship appeared to be non-linear.

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REFERENCES

Chang, B.D., Page, F.H., Losier, R.J., McCurdy, E.P., and MacKeigan, K.G. 2011. Characterization of the spatial pattern of benthic sulfide concentrations at six salmon farms in southwestern New Brunswick, Bay of Fundy. Can. Tech. Rep. Fish. Aquat. Sci. 2915: iv + 24 p.

Hanke, A.R. 2010. Open Ocean Aquaculture Research Project Phase II. Report to the Atlantic Canada Fish Farmers Association, Letang, NB. 49 p.

Hargrave, B.T. 2010. Empirical relationships describing benthic impacts of salmon aquaculture. Aquacult. Environ. Interact. 1: 33-46.

NBDELG (New Brunswick Department of Environment and Local Government). 2012a. The Environmental Management Program for the Marine Finfish Cage Aquaculture Industry in New Brunswick, version 3.0. New Brunswick Department of Environment and Local Government, Fredericton, NB. 19 p.

NBDELG (New Brunswick Department of Environment and Local Government). 2012b. Standard Operating Practices for the Environmental Monitoring of the Marine Finfish Cage Aquaculture Industry in New Brunswick, July 2012. New Brunswick Department of Environment and Local Government, Fredericton, NB. 24 p.

NBDENV (New Brunswick Department of Environment). 2007. Standard Operating Practices for the Environmental Monitoring of the Marine Finfish Cage Aquaculture Industry in New Brunswick, July 2007. New Brunswick Department of Environment, Fredericton, NB. 24 p.

NBDENV (New Brunswick Department of Environment). 2010. Standard Operating Practices for the Environmental Monitoring of the Marine Finfish Cage Aquaculture Industry in New Brunswick, July 2010. New Brunswick Department of Environment, Fredericton, NB. 24 p.

Page, F.H., Chang, B.D., Losier, R.J., McCurdy, E.P., Reid, J.C.E., and Hanke, A.R. 2011. Temporal variations in sediment sulfide levels under marine salmon farms in southwestern New Brunswick, Bay of Fundy, during the annual environmental monitoring period. Aquacul. Assoc. Canada Spec. Publ. 17: 64-66.

Wildish, D.J., Akagi, H.M., Hamilton, N., and Hargrave, B.T. 1999. A recommended method for monitoring sediments to detect organic enrichment from mariculture in the Bay of Fundy. Can. Tech. Rep. Fish. Aquat. Sci. 2286: iii + 31 p.

Table 1. Site classification based on mean sediment sulfide concentration (total S^{2-}) in annual monitoring of finfish farms in southwestern New Brunswick. Based on NBDELG (2012a).

Site classification	Sediment sulfide (total S^{2-}) (μM)	Effects on marine sediments
Oxic A	<750	Low effects
Oxic B	750-1 499	Low effects
Hypoxic A	1 500-2 999	May be causing adverse effects
Hypoxic B	3 000-4 499	Likely causing adverse effects
Hypoxic C	4 500-5 999	Causing adverse effects
Anoxic	>6 000	Causing severe damage

Table 2. Water depths, stocking information, monitoring dates, and biomass estimates for SWNB salmon farms conducting Tier 2 monitoring during 2007-2011. Depths are averages under the cage array (relative to lowest normal tide; from Canadian Hydrographic Service field sheets). Other information was obtained from the New Brunswick Department of Agriculture, Aquaculture and Fisheries; the New Brunswick Department of Environment and Local Government; monitoring reports; and farm operators. n/a = data not available.

Site	Depth under cage array (m)	Smolt year-class	Month of maximum biomass	Month of end of harvest	Tier 1 date	Biomass (kg) at Tier 1	Tier 2 date	Biomass (kg) at Tier 2
MF-010	6.8	spring-06[1]	Feb-08	Mar-08	21-Aug-07	342 900	17/19-Sep-07	421 900
MF-061	18.5	Apr-06	n/a	Mar-08	31-Aug-07	n/a	24/25-Sep-07	n/a
MF-342	15.1	Jun-06	Oct-07	Mar-08	25-Oct-07	868 500	02-Nov-07	n/a
MF-002	9.6	spring-07	Feb-09	May-09	13-Aug-08	n/a	28/29-Aug-08	862 200
MF-037	18.8	Oct-07	Jul-09	Oct-09	24-Sep-08	529 600	05/09-Oct-08	592 700
MF-186	14.0	spring-07	n/a	n/a	14-Oct-08	n/a[2]	05-Nov-08	n/a[2]
MF-502	24.6	Jul-Sep-06[3]	Feb-08	Sep-08	25-Oct-08	0	08/09-Nov-08	0
MF-026	20.9	Nov-Dec-07	Nov-09	Feb-10	28-Aug-09	1 831 300	11/16-Sep-09	1 775 500
MF-251	32.2	Jun-09	Jul-11	Oct-11	23-Sep-10	974 400	12-Oct-10	1 026 400
MF-342	15.1	May-09	Jul-10	Jul-11	18-Aug-10	587 700	08-Sep-10	463 700
MF-053	18.0	spring-09	Jul-11	Sep-11	27-Oct-11	0	17-Nov-11	0
MF-215	11.9	fall-09	Oct-11[4]	Feb-12	14-Oct-11	1 892 600	18-Oct-11	1 655 400
MF-251	32.2	Jun-09	n/a	Oct-11[5]	19-Oct-11	0	01-Nov-11	0
MF-342	15.1	May-09	Jul-10	Jul-11	26-Oct-11	0	09-Nov-11	0

[1] fish were originally stocked at another farm in the spring of 2006; then moved to MF-010 in November 2006.
[2] number of fish on site at MF-186 at Tier 1 monitoring ≅ 140 000.
[3] fish were originally stocked at another farm in 2006; then moved to MF-502 in the fall of 2007.
[4] harvesting began at MF-215 on the date of Tier 1 monitoring (14 October 2011).
[5] harvesting at MF-251 was completed in early October 2011, just before Tier 1 monitoring.

Table 3. Sediment sulfide concentrations in Tier 1 and corresponding Tier 2 monitoring at SWNB salmon farms during 2007-2011. n = number of monitoring stations (triplicate samples taken at each station).

	Tier 1 monitoring				Tier 2 monitoring						
						All Tier 2 stations			Tier 1 stations		
Site	Date	n	Mean sulfide (μM)	Classification	Date	n	Mean sulfide (μM)	Classification	n	Mean sulfide (μM)	Classification
MF-010	21-Aug-07	3	3 252	Hyp B	17/19-Sep-07	89	1 304	Oxic B	3	1 824	Hyp B
MF-061	31-Aug-07	3	4 291	Hyp B	24/25-Sep-07	64	2 859	Hyp A	3	3 712	Hyp B
MF-342	25-Oct-07	2	9 468	Anoxic	02-Nov-07	39	1 498	Oxic B	2	2 915	Hyp B
MF-002	13-Aug-08	4	3 839	Hyp B	28/29-Aug-08	57	2 354	Hyp A	4	3 347	Hyp B
MF-037	24-Sep-08	4	5 227	Hyp C	05/09-Oct-08	48	2 647	Hyp A	4	4 787	Hyp C
MF-186	14-Oct-08	2	5 672	Hyp C	05-Nov-08	15	595	Oxic A	2	507	Oxic A
MF-502	25-Oct-08	2	4 095	Hyp B	08/09-Nov-08	36	1 083	Oxic B	2	4 262	Hyp B
MF-026	28-Aug-09	5	8 169	Anoxic	11/16-Sep-09	88	4 801	Hyp C	5	5 929	Hyp C
MF-251	23-Sep-10	4	5 092	Hyp C	12-Oct-10	39	2 314	Hyp A	4	2 156	Hyp A
MF-342	18-Aug-10	2	7 188	Anoxic	08-Sep-10	46	4 243	Hyp B	2	7 372	Anoxic
MF-053	27-Oct-11	3	3 574	Hyp B	17-Nov-11	41	1 662	Hyp A	3	2 117	Hyp A
MF-215	14-Oct-11	4	3 777	Hyp B	18-Oct-11	48	3 120	Hyp B	4	1 720	Hyp A
MF-251	19-Oct-11	4	4 036	Hyp B	01-Nov-11	39	1 180	Oxic B	4	445	Oxic A
MF-342	26-Oct-11	2	3 293	Hyp B	09-Nov-11	46	5 884	Hyp C	2	5 420	Hyp C

Table 4. Mean sulfide concentrations per monitoring event, with mean, minimum, and maximum standard deviations (SD) and coefficients of variation (CV) per station, in Tier 1 (top) and corresponding Tier 2 (bottom) monitoring events at SWNB salmon farms, 2007-2011. SDs and CVs were calculated for the triplicate samples taken at each monitoring station. n = number of monitoring stations. CV (%) = (SD/mean) × 100.

Tier 1			Site mean	SD per station			CV (%) per station		
Site	Year	n	(µM)	Mean	Min.	Max.	Mean	Min.	Max.
MF-010	2007	3	3 252	716	425	1 033	22.9	15.5	35.1
MF-061	2007	3	4 291	498	131	870	10.9	5.7	18.5
MF-342	2007	2	9 468	3 754	1 230	6 277	36.2	15.6	56.9
MF-002	2008	4	3 839	1 250	555	2 054	41.5	13.0	93.9
MF-037	2008	4	5 227	1 862	967	2 675	35.1	26.8	42.3
MF-186	2008	2	5 672	2 758	2 257	3 258	63.7	28.0	99.4
MF-502	2008	2	4 095	905	802	1 009	22.6	20.4	24.8
MF-026	2009	5	8 169	1 846	208	2 885	25.2	2.0	41.0
MF-251	2010	4	5 092	1 938	826	3 349	40.6	17.3	73.9
MF-342	2010	2	7 188	3 631	3 178	4 085	50.5	44.2	56.8
MF-053	2011	3	3 574	996	102	2 418	24.4	11.7	32.8
MF-215	2011	4	3 777	1 798	103	5 976	40.0	20.0	53.3
MF-251	2011	4	4 036	1 433	264	4 608	39.8	22.6	76.6
MF-342	2011	2	3 293	1 026	556	1 496	29.7	19.8	39.6

Tier 2			Site mean	SD per station			CV (%) per station		
Site	Year	n	(µM)	Mean	Min.	Max.	Mean	Min.	Max.
MF-010	2007	89	1 304	192	16	718	18.4	5.0	66.4
MF-061	2007	64	2 859	342	54	1 513	12.7	3.7	26.8
MF-342	2007	39	1 498	655	47	3 094	42.5	4.2	124.6
MF-002	2008	57	2 354	556	37	1 969	27.9	4.1	83.4
MF-037	2008	48	2 647	768	45	2 372	33.8	6.5	72.6
MF-186	2008	15	595	224	10	1 118	47.0	17.9	94.9
MF-502	2008	36	1 083	202	7	1 107	33.6	9.0	69.3
MF-026	2009	88	4 801	890	261	2 410	21.0	3.0	54.0
MF-251	2010	39	2 314	478	31	2 414	22.0	3.0	57.0
MF-342	2010	46	4 243	761	90	2 325	24.1	1.6	67.8
MF-053	2011	41	1 662	348	61	1 996	20.2	5.4	43.0
MF-215	2011	48	3 120	1 153	37	5 931	53.3	4.4	157.3
MF-251	2011	39	1 180	464	46	4 102	40.7	7.2	161.9
MF-342	2011	46	5 884	1 061	70	2 912	19.7	2.3	47.5

Table 5. Comparisons of sediment sulfide concentrations in Tier 1 vs. Tier 2 monitoring at SWNB salmon farms, 2007-2011. Comparisons were made using individual sample data collected in Tier 1 and Tier 2 monitoring (triplicate samples at each station). n = number of monitoring stations; S = significant (α=0.05, 2-tailed); NS = not significant.

	Tier 1 monitoring			Tier 2 monitoring					
Site	Date	n	Mean sulfide (µM)	Date	n	Mean sulfide (µM)	Prob.	Sig.	Days between Tier 1 & 2
MF-010	21-Aug-07	3	3 252	17/19-Sep-07	89	1 304	0.000	S	27-29
MF-061	31-Aug-07	3	4 291	24/25-Sep-07	64	2 859	0.011	S	24-25
MF-342	25-Oct-07	2	9 468	02-Nov-07	39	1 498	0.000	S	8
MF-002	13-Aug-08	4	3 839	28/29-Aug-08	57	2 354	0.017	S	15-16
MF-037	24-Sep-08	4	5 227	05/09-Oct-08	48	2 647	0.000	S	11-15
MF-186	14-Oct-08	2	5 672	05-Nov-08	15	595	0.009	S	22
MF-502	25-Oct-08	2	4 095	08/09-Nov-08	36	1 083	0.001	S	14-15
MF-026	28-Aug-09	5	8 169	11/16-Sep-09	88	4 801	0.000	S	14-19
MF-251	23-Sep-10	4	5 092	12-Oct-10	39	2 314	0.000	S	19
MF-342	18-Aug-10	2	7 188	08-Sep-10	46	4 243	0.042	S	21
MF-053	27-Oct-11	3	3 574	17-Nov-11	41	1 662	0.780	NS	21
MF-215	14-Oct-11	4	3 777	18-Oct-11	48	3 120	0.813	NS	4
MF-251	19-Oct-11	4	4 036	01-Nov-11	39	1 180	0.003	S	13
MF-342	26-Oct-11	2	3 293	09-Nov-11	46	5 884	0.110	NS	14

Table 6. Comparisons of sediment sulfide concentrations in Tier 1 monitoring vs. corresponding stations in Tier 2 monitoring at SWNB salmon farms, 2007-2011. Comparisons were made using individual sample data collected in Tier 1 monitoring and corresponding Tier 2 stations (triplicate samples at each station). n = number of monitoring stations; S = significant (α=0.05, 2-tailed); NS = not significant.

	Tier 1 monitoring			Corresponding Tier 2 monitoring stations				
Site	Date	n	Mean sulfide (µM)	Date	n	Mean sulfide (µM)	Prob.	Sig.
MF-010	21-Aug-07	3	3 252	17/19-Sep-07	3	1 824	0.029	S
MF-061	31-Aug-07	3	4 291	24/25-Sep-07	3	3 712	0.627	NS
MF-342	25-Oct-07	2	9 468	02-Nov-07	2	2 915	0.004	S
MF-002	13-Aug-08	4	3 839	28/29-Aug-08	4	3 348	0.488	NS
MF-037	24-Sep-08	4	5 227	05/09-Oct-08	4	4 787	0.603	NS
MF-186	14-Oct-08	2	5 672	05-Nov-08	2	507	0.055	NS
MF-502	25-Oct-08	2	4 095	08/09-Nov-08	2	4 262	0.873	NS
MF-026	28-Aug-09	5	8 169	11/16-Sep-09	5	5 929	0.019	S
MF-251	23-Sep-10	4	5 092	12-Oct-10	4	2 156	0.001	S
MF-342	18-Aug-10	2	7 188	08-Sep-10	2	7 372	0.631	NS
MF-053	27-Oct-11	3	3 574	27-Nov-11	3	2 117	0.895	NS
MF-215	14-Oct-11	4	3 777	18-Oct-11	4	1 720	0.488	NS
MF-251	19-Oct-11	4	4 036	01-Nov-11	4	445	0.001	S
MF-342	26-Oct-11	2	3 293	09-Nov-11	2	3 915	0.262	NS

Table 7. Comparisons of sediment sulfide concentrations in Tier 2 monitoring data collected at Tier 1 stations vs. all other Tier 2 stations at SWNB salmon farms, 2007-2011. Comparisons were made using individual sample data collected in Tier 2 monitoring (triplicate samples at each station). n = number of monitoring stations; S = significant (α=0.05, 2-tailed); NS = not significant.

		Tier 2 data at Tier 1 stations		All other Tier 2 stations			
Site	Tier 2 date	n	Mean sulfide (µM)	N	Mean sulfide (µM)	Prob.	Sig.
MF-010	17/19-Sep-07	3	1 824	86	1 286	0.053	NS
MF-061	24/25-Sep-07	3	3 712	61	2 817	0.067	NS
MF-342	02-Nov-07	2	2 915	37	1 421	0.007	S
MF-002	28/29-Aug-08	4	3 347	53	2 279	0.090	NS
MF-037	05/09-Oct-08	4	4 787	44	2 452	0.000	S
MF-186	05-Nov-08	2	507	13	608	0.317	NS
MF-502	08/09-Nov-08	2	4 262	34	896	0.001	S
MF-026	11/16-Sep-09	5	5 929	83	4 733	0.038	S
MF-251	12-Oct-10	4	2 156	35	2 332	0.269	NS
MF-342	08-Sep-10	2	7 372	44	4 099	0.007	S
MF-053	17-Nov-11	3	2 117	38	1 626	0.484	NS
MF-215	18-Oct-11	4	1 720	44	3 248	0.472	NS
MF-251	01-Nov-11	4	445	35	1 262	0.011	S
MF-342	09-Nov-11	2	3 915	44	5 973	0.294	NS

Table 8. Summary table of comparisons of Tier 1 vs. Tier 2 sediment sulfide monitoring results at SWNB salmon farms, 2007-2011. S = significant (α=0.05, 2-tailed); NS = not significant.

Site	Year	Tier 1 (all) vs. Tier 2 (all) (Table 5)	Tier 1 (all) vs. corresponding Tier 2 stations (Table 6)	Tier 2 only: Tier 1 stations vs. all other stations (Table 7)
MF-010	2007	S	S	NS
MF-061	2007	S	NS	NS
MF-342	2007	S	S	S
MF-002	2008	S	NS	NS
MF-037	2008	S	NS	S
MF-186	2008	S	NS	NS
MF-502	2008	S	NS	S
MF-026	2009	S	S	S
MF-251	2010	S	S	NS
MF-342	2010	S	NS	S
MF-053	2011	NS	NS	NS
MF-215	2011	NS	NS	NS
MF-251	2011	S	S	S
MF-342	2011	NS	NS	NS

Table 9. Comparisons of sediment sulfide concentrations at all "cage edge" monitoring stations vs. all "between cage" stations during Tier 2 monitoring at SWNB salmon farms, 2007-2011. Comparisons were made using individual sample data from Tier 2 monitoring (triplicate samples at each station). n = number of monitoring stations; S = significant (α=0.05, 2-tailed); NS = not significant.

		"Cage edge" stations		"Between cage" stations			
Site	Tier 2 date	n	Mean sulfide (µM)	n	Mean sulfide (µM)	Prob.	Sig.
MF-010	17/19-Sep-07	33	1 842	56	987	0.000	S
MF-061	24/25-Sep-07	30	2 655	34	3 039	0.075	NS
MF-342	02-Nov-07	22	1 685	17	1 255	0.026	S
MF-002	28/29-Aug-08	26	3 498	31	1 395	0.000	S
MF-037	05/09-Oct-08	25	3 084	23	2 172	0.002	S
MF-186	05-Nov-08	12	549	3	776	0.681	NS
MF-502	08/09-Nov-08	25	1 093	11	1 063	0.608	NS
MF-026	11/16-Sep-09	36	4 734	52	4 848	0.578	NS
MF-251	12-Oct-10	22	2 190	17	2 473	0.299	NS
MF-342	08-Sep-10	24	4 567	22	3 899	0.142	NS
MF-053	17-Nov-11	23	1 723	18	1 584	0.586	NS
MF-215	18-Oct-11	24	3 482	24	2 759	0.595	NS
MF-251	01-Nov-11	22	1 366	17	938	0.025	S
MF-342	09-Nov-11	24	5 878	22	5 891	0.635	NS

Table 10. Paired comparisons of mean sediment sulfide concentrations at "cage edge" stations vs. adjacent "between cage" stations during Tier 2 monitoring at SWNB salmon farms, 2007-2011. Comparisons were made where there were "cage edge" and adjacent "between cage" stations in close proximity: at most sites, these included only the "inner" stations at corner cages (see Fig. 6-19). n = number of monitoring stations (triplicate samples at each station); S = significant (α=0.05, 2-tailed); NS = not significant. At MF-186, there was an insufficient number of stations for statistical testing.

			Mean sulfide (µM)			
Site	Tier 2 date	n	"Cage edge" stations	"Between cage" stations	Prob.	Sig.
MF-010	17/19-Sep-07	8	1 749	1 130	0.093	NS
MF-061	24/25-Sep-07	6	2 841	2 915	0.753	NS
MF-342	02-Nov-07	8	1 475	1 121	0.401	NS
MF-002	28/29-Aug-08	8	3 110	1 484	0.036	S
MF-037	05/09-Oct-08	7	3 687	2 081	0.043	S
MF-186	05-Nov-08	2	622	1 135	-	-
MF-502	08/09-Nov-08	7	1 878	1 767	0.612	NS
MF-026	11/16-Sep-09	8	4 567	4 821	0.575	NS
MF-251	12-Oct-10	8	2 151	3 367	0.327	NS
MF-342	08-Sep-10	8	4 024	3 936	0.575	NS
MF-053	17-Nov-11	7	2 234	1 719	0.612	NS
MF-215	18-Oct-11	8	4 778	2 495	0.401	NS
MF-251	01-Nov-11	8	1 387	662	0.575	NS
MF-342	09-Nov-11	8	5 137	4 762	0.401	NS

Table 11. Calculated seafloor areas within contour intervals, based on sediment sulfide concentration data collected in Tier 2 monitoring at SWNB salmon farms, 2007-2011 (see Fig. 6 to 19).

Classification	Sulfide concentration (µM)	Seafloor area (m^2)						
		MF-010 (2007)	MF-061 (2007)	MF-342 (2007)	MF-002 (2008)	MF-037 (2008)	MF-186 (2008)	MF-502 (2008)
Oxic A	<750	22 400	100	7 000	5 700	2 700	8 500	22 200
Oxic B	750-1 500	13 200	3 200	8 200	6 600	4 200	3 200	1 300
Hypoxic A	1 500-3 000	11 500	17 800	4 000	12 800	24 900	1 500	2 700
Hypoxic B	3 000-4 500	3 000	10 300	1 900	2 700	12 200	0	2 900
Hypoxic C	4 500-6 000	200	2 500	100	1 700	2 100	0	900
Anoxic	>6 000	0	300	0	1 600	300	0	0
≥Hypoxic A	>1 500	14 600	30 900	6 000	18 800	39 400	1 500	6 500
(% of total)		(29%)	(91%)	(28%)	(60%)	(85%)	(11%)	(22%)
≥Hypoxic B	>3 000	3 100	13 000	2 000	6 000	14 500	0	3 800
(% of total)		(6%)	(38%)	(10%)	(19%)	(31%)	(0%)	(13%)

Classification	Sulfide concentration (µM)	Seafloor area (m^2)						
		MF-026 (2009)	MF-251 (2010)	MF-342 (2010)	MF-053 (2011)	MF-215 (2011)	MF-251 (2011)	MF-342 (2011)
Oxic A	<750	0	900	0	500	5 700	21 800	0
Oxic B	750-1 500	100	17 000	2 300	25 200	9 000	13 200	500
Hypoxic A	1 500-3 000	6 700	18 400	6 000	21 100	12 700	4 400	3 300
Hypoxic B	3 000-4 500	22 400	3 300	6 100	1 400	4 000	1 100	5 300
Hypoxic C	4 500-6 000	16 400	1 100	7 900	100	2 400	300	4 900
Anoxic	>6 000	14 700	1 100	3 500	0	5 600	900	8 700
≥Hypoxic A	>1 500	60 300	23 900	23 400	22 600	24 800	6 600	22 200
(% of total)		(>99%)	(57%)	(91%)	(47%)	(63%)	(16%)	(98%)
≥Hypoxic B	>3 000	53 500	5 500	17 500	1 500	12 000	2 300	18 900
(% of total)		(89%)	(13%)	(68%)	(3%)	(31%)	(5%)	(83%)

Table 12. Relationships between sediment sulfide concentration and oxidation-reduction (redox) potential at salmon farms. x = total dissolved sulfide concentration (μM S^{2-}); y = redox potential (mV_{NHE}). Hargrave (2010) equation 1 is a non-linear exponential relationship derived from data from SWNB and British Columbia; all other equations are linear relationships for data collected in SWNB.

Data source	Equation	r^2
Tier 2 data (this study)	$y = 278 - 47 \times \ln(x)$	0.39
Hargrave (2010): equation 1 (non-linear)	$y = -209 + 444 \times e^{-x/2025}$	0.99
Hargrave (2010): equation 2	$y = 473 - 66 \times \ln(x)$	0.67
Wildish et al. (1999): 1998 data	$y = 495 - 59 \times \ln(x)$	0.60

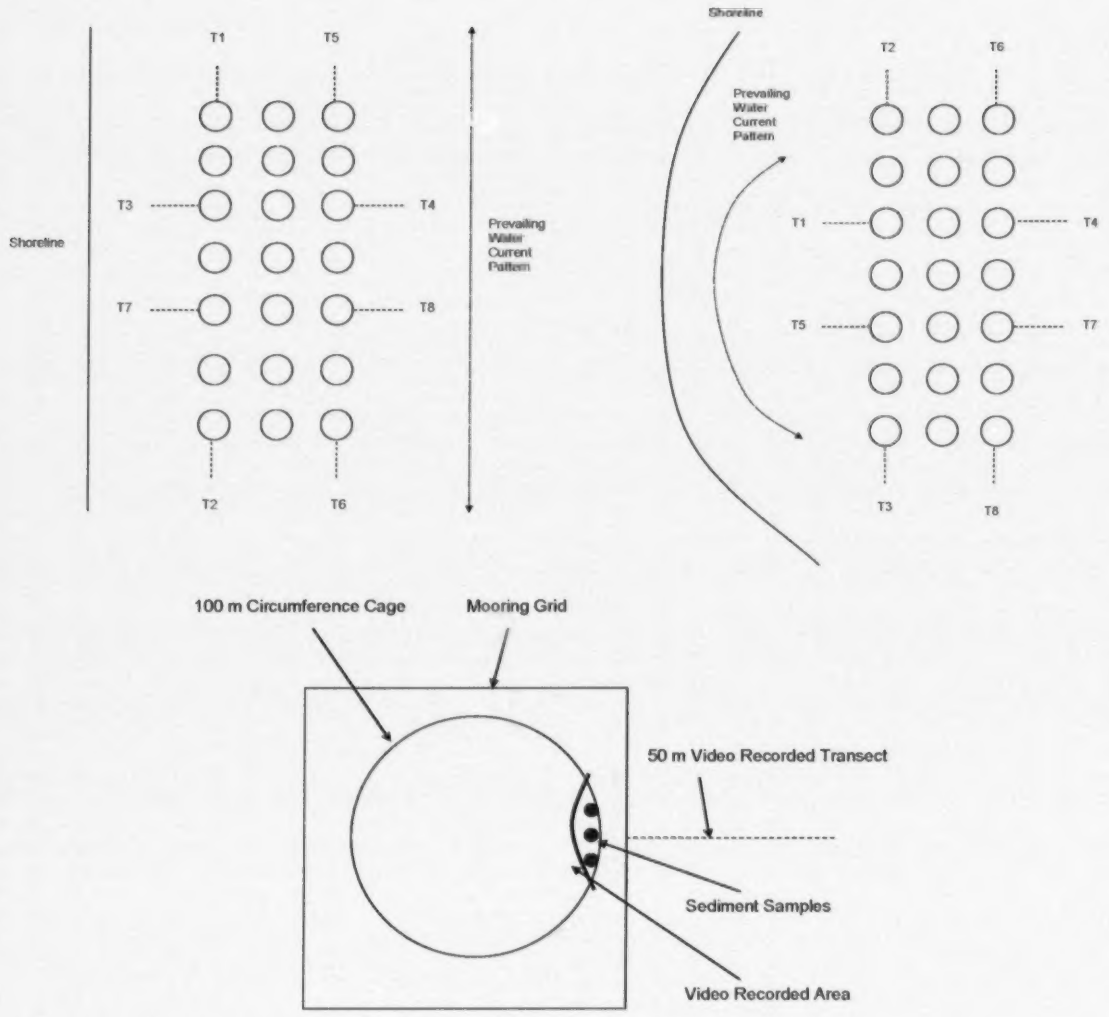

Fig. 1. Locations of transects and samples for Tier 1 monitoring in the Environmental Management Program for the Marine Finfish Cage Aquaculture Industry in New Brunswick, since 2006 (from NBDELG 20012b). Top left: transect locations for sites with generally linear water current patterns and moderate or high current speeds. Top right: transect locations for sites with generally curving water current patterns or low current speeds. Bottom: close-up of a cage showing locations of 3 sediment samples taken at the cage edge (within 1 m^2, in similar substrate types) for each transect.

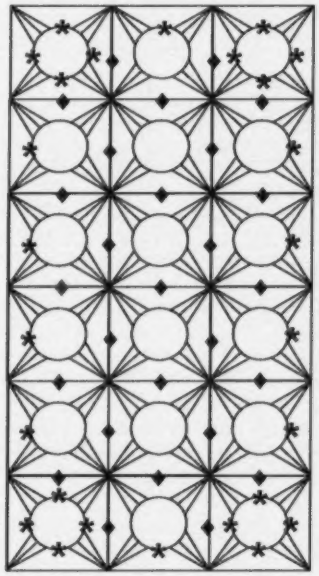

Fig. 2. Locations of samples for Tier 2 monitoring in the Environmental Management Program for the Marine Finfish Aquaculture Industry in New Brunswick, since 2007 (from NBDELG 2012b). Triplicate samples are taken at each station marked by * (cage edges) and ♦ (between cages). Large circles represent cages.

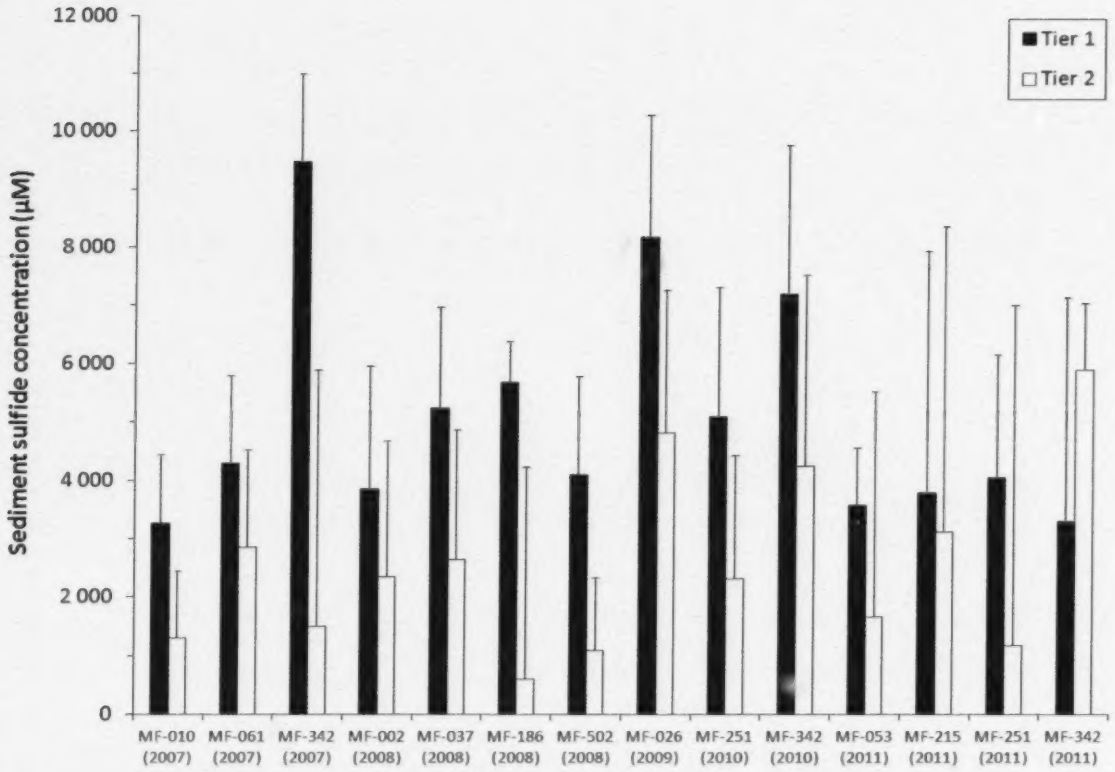

Fig. 3. Sulfide concentrations in Tier 1 and Tier 2 monitoring at SWNB salmon farms that conducted Tier 2 monitoring during 2007-2011. Tier 2 monitoring is required when the mean sulfide concentration in Tier 1 monitoring exceeds 3000 µM. Bars represent mean sediment sulfide concentrations for all samples in each monitoring event; vertical lines represent one standard deviation (for all samples in each monitoring event).

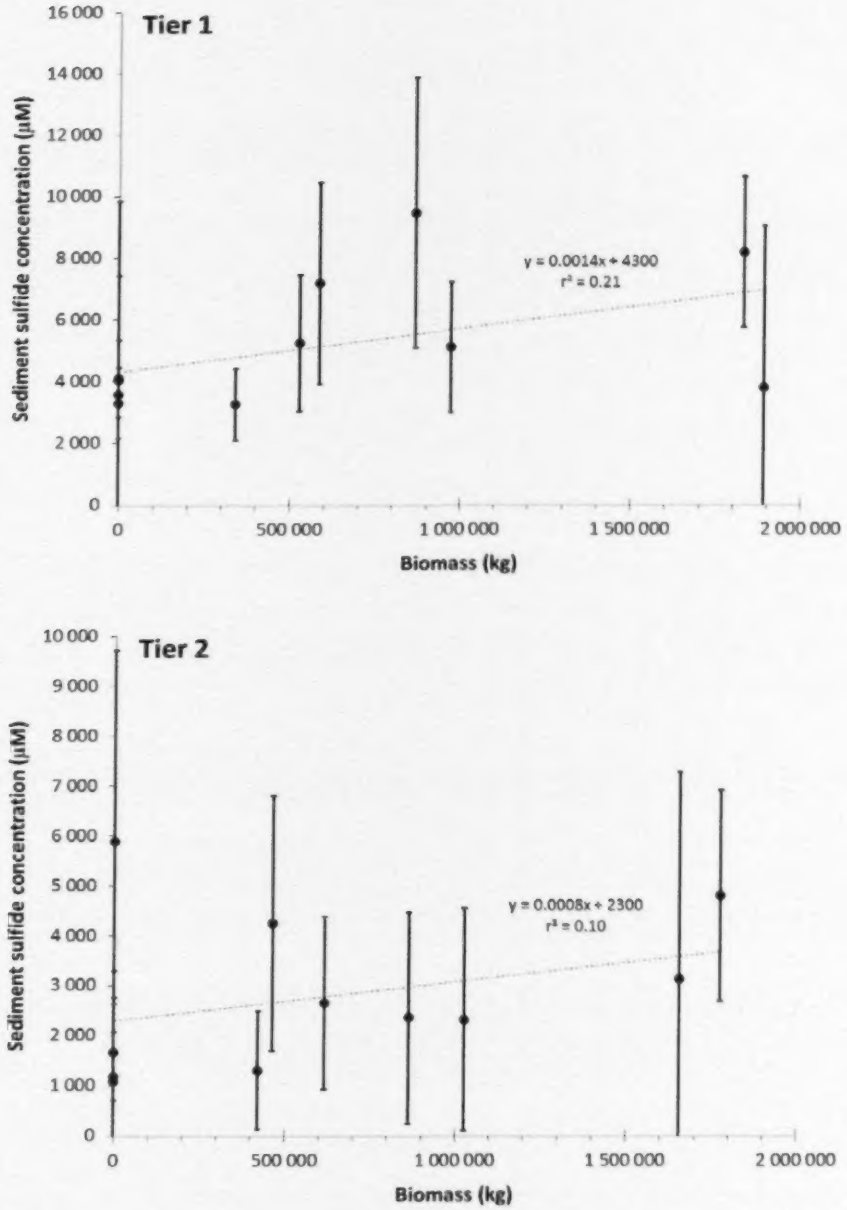

Fig. 4. Relationship between the biomass of fish on site and the mean sediment sulfide concentration in Tier 2 monitoring events at SWNB salmon farms, 2007-2011 (bottom), and in Tier 1 monitoring events at the same sites in the same years (top). Biomass data were available for 11 of the 14 Tier 2 monitoring events, and for 11 of the corresponding Tier 1 monitoring events (see Table 2). Each point represents the mean sulfide concentration at one monitoring event; vertical lines represent ± one standard deviation for all samples in each monitoring event.

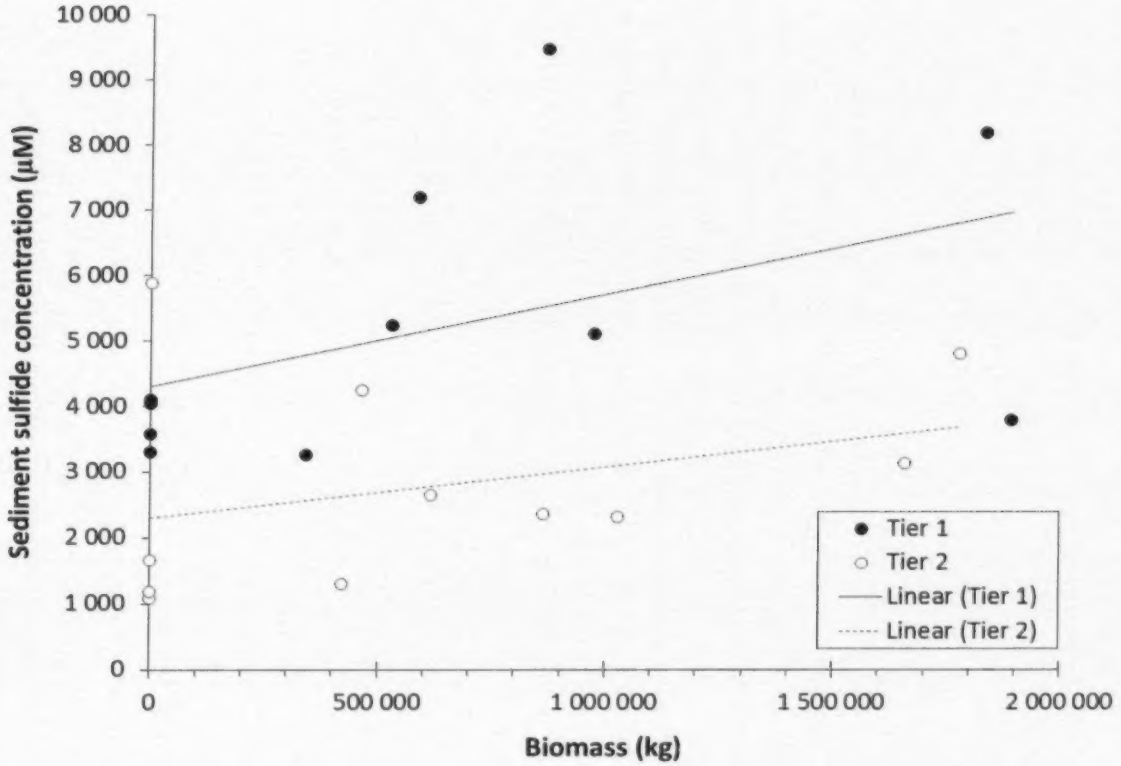

Fig. 5. Relationships between the biomass of fish on site and the mean sediment sulfide concentration in Tier 2 and corresponding Tier 1 monitoring events at SWNB salmon farms, 2007-2011. The points and lines are the same as in Fig. 4.

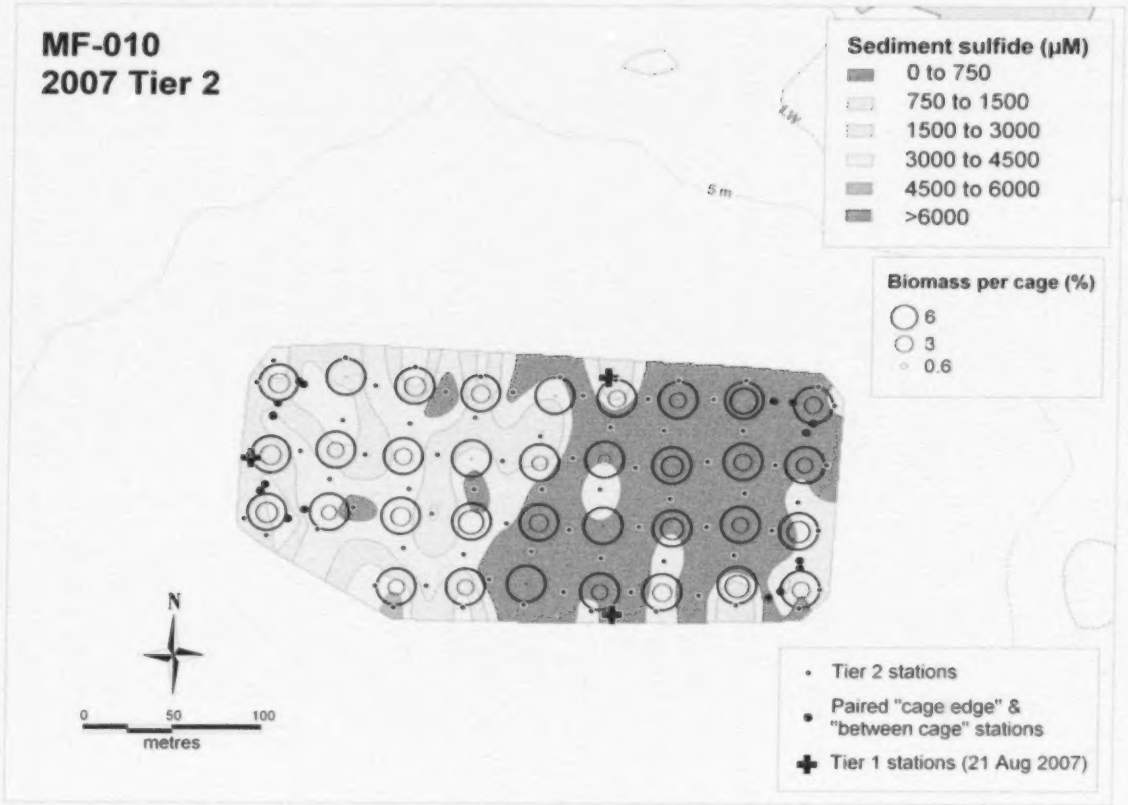

Fig. 6. Contour plot of sediment sulfide concentrations from Tier 2 monitoring at site MF-010 on 17-19 September 2007. Large circles indicate cage sizes and approximate locations (thirty-four 70-m circumference cages). Smaller circles inside the cages represent the percent of the total biomass (421 900 kg) in each cage at the time of Tier 2 monitoring: the fish biomass was unevenly distributed among the cages, with 5 cages holding no fish, and each of the other 29 cages holding 1.5-6.4% of the total biomass. The average depth under the contoured area was approximately 6.8 m below chart datum (lowest normal tide).

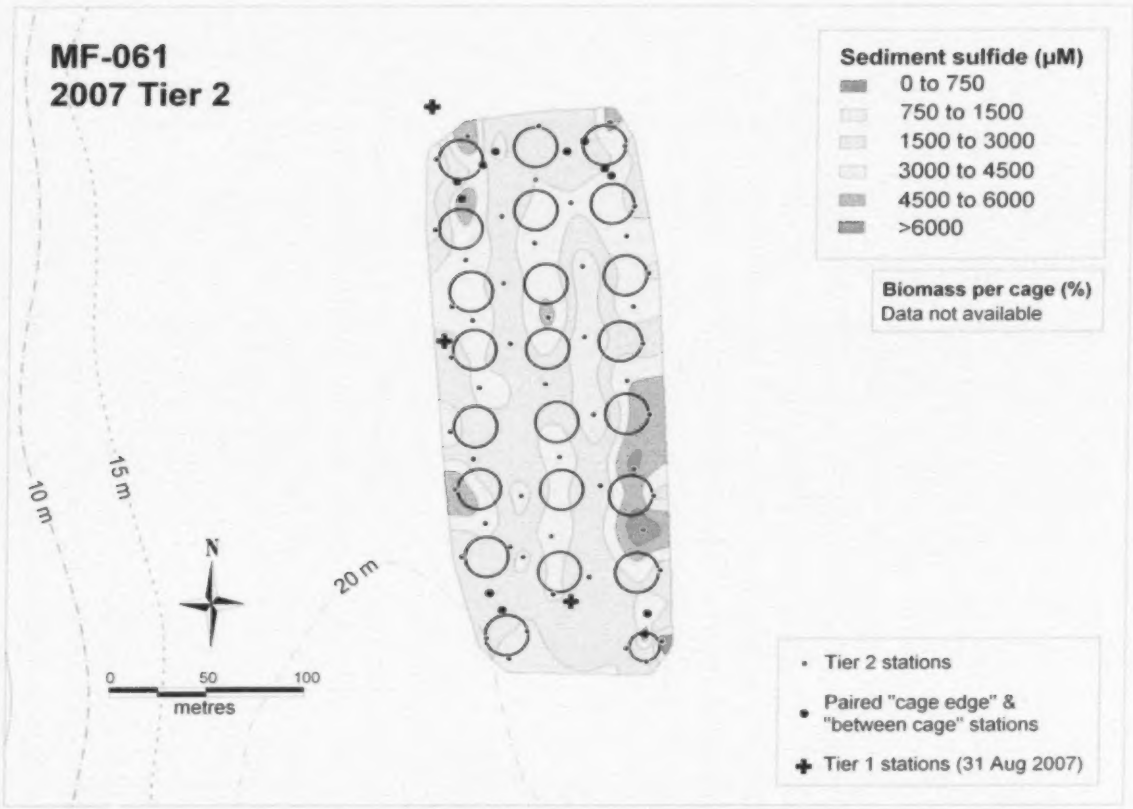

Fig. 7. Contour plot of sediment sulfide concentrations from Tier 2 monitoring at site MF-061 on 24-25 September 2007. Circles indicate cage sizes and approximate locations (twenty-two 70-m circumference cages, plus one 50-m cage). Data on the total fish biomass and the distribution of the biomass among the cages at the time of Tier 2 monitoring were not available. The average depth under the contoured area was approximately 18.5 m below chart datum (lowest normal tide).

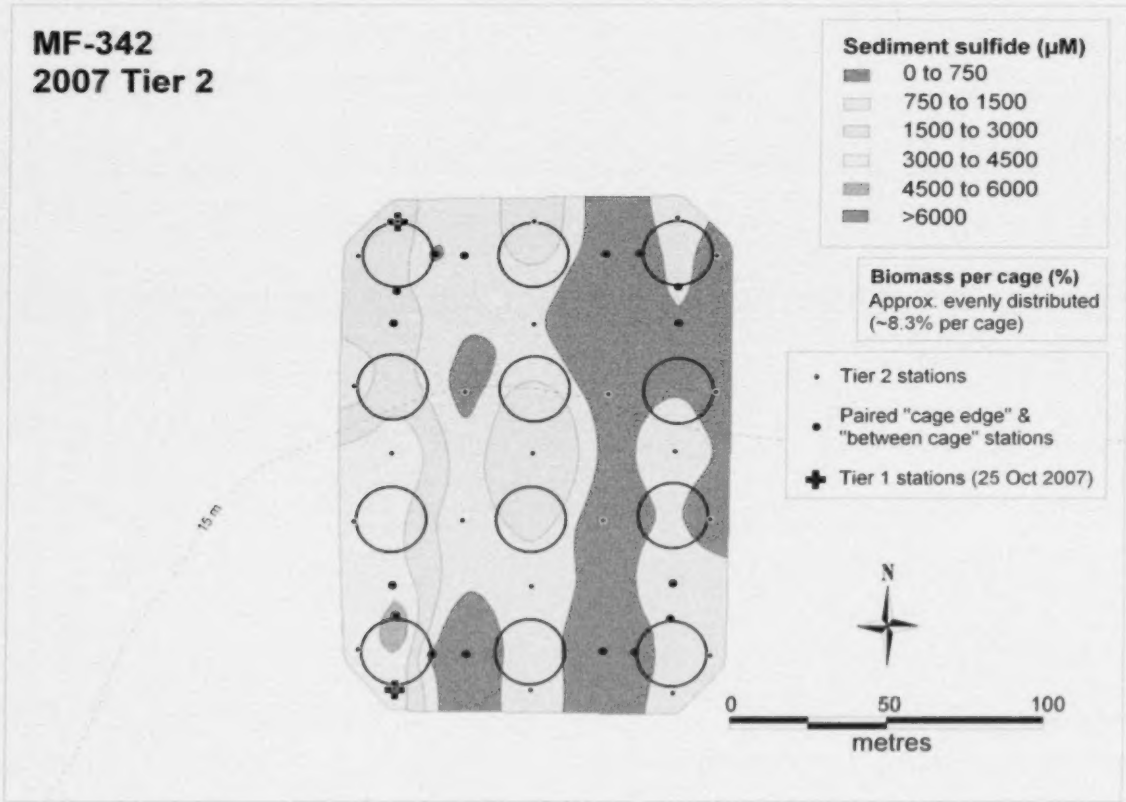

Fig. 8. Contour plot of sediment sulfide concentrations from Tier 2 monitoring at site MF-342 on 2 November 2007. Circles indicate cage sizes and approximate locations (twelve 70-m circumference cages). The Tier 1 monitoring report indicated that there were 192 000 fish on site (on 25 October 2007), with the biomass (868 500 kg total) evenly distributed among the 12 cages (8.3% per cage; actual biomass data were not available). Tier 1 station locations are approximate, based on the aerial photo provided in the Tier 1 report (the coordinates provided in the Tier 1 report were incorrect). The average depth under the contoured area was approximately 15.1 m below chart datum (lowest normal tide).

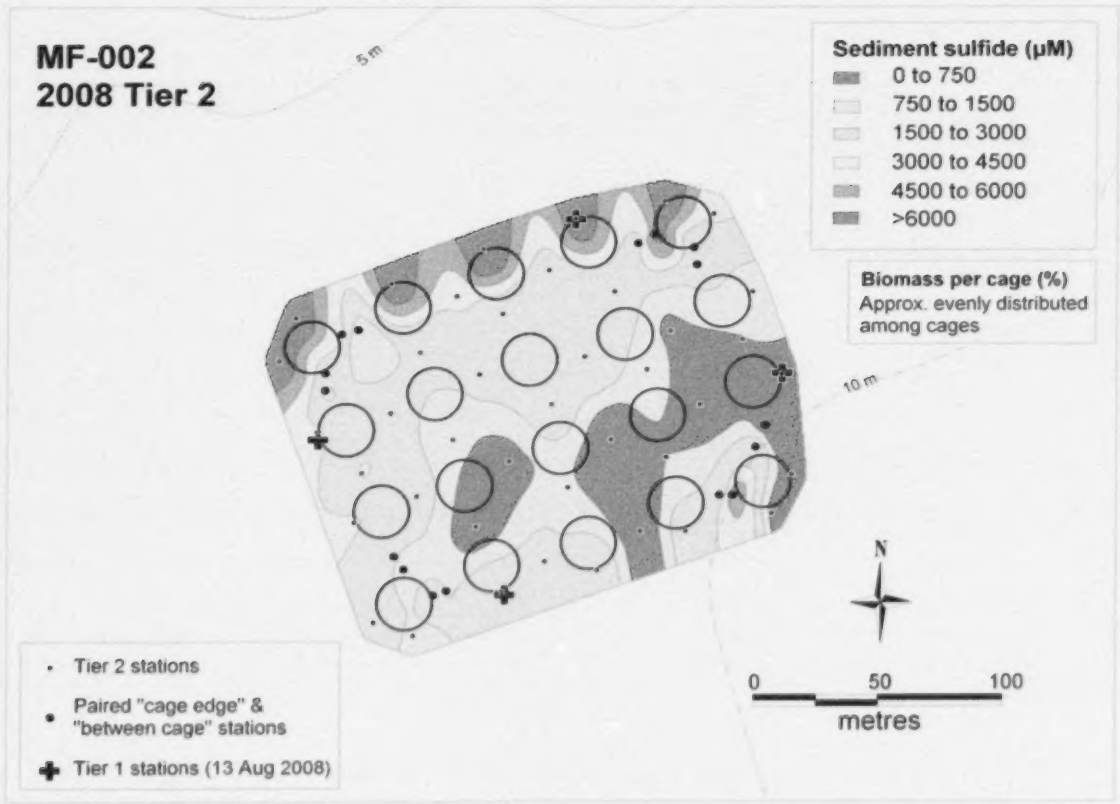

Fig. 9. Contour plot of sediment sulfide concentrations from Tier 2 monitoring at site MF-002 on 28-29 August 2008. Circles indicate cage sizes and approximate locations (twenty 70-m circumference cages). The Tier 2 monitoring report indicated that the fish biomass (862 200 kg total) was evenly distributed among the cages (actual biomass per cage data were not available). Tier 1 station locations are approximate, based on the aerial photo provided in the Tier 1 report (the coordinates provided in the Tier 1 report were incorrect). The average depth under the contoured area was approximately 9.6 m below chart datum (lowest normal tide).

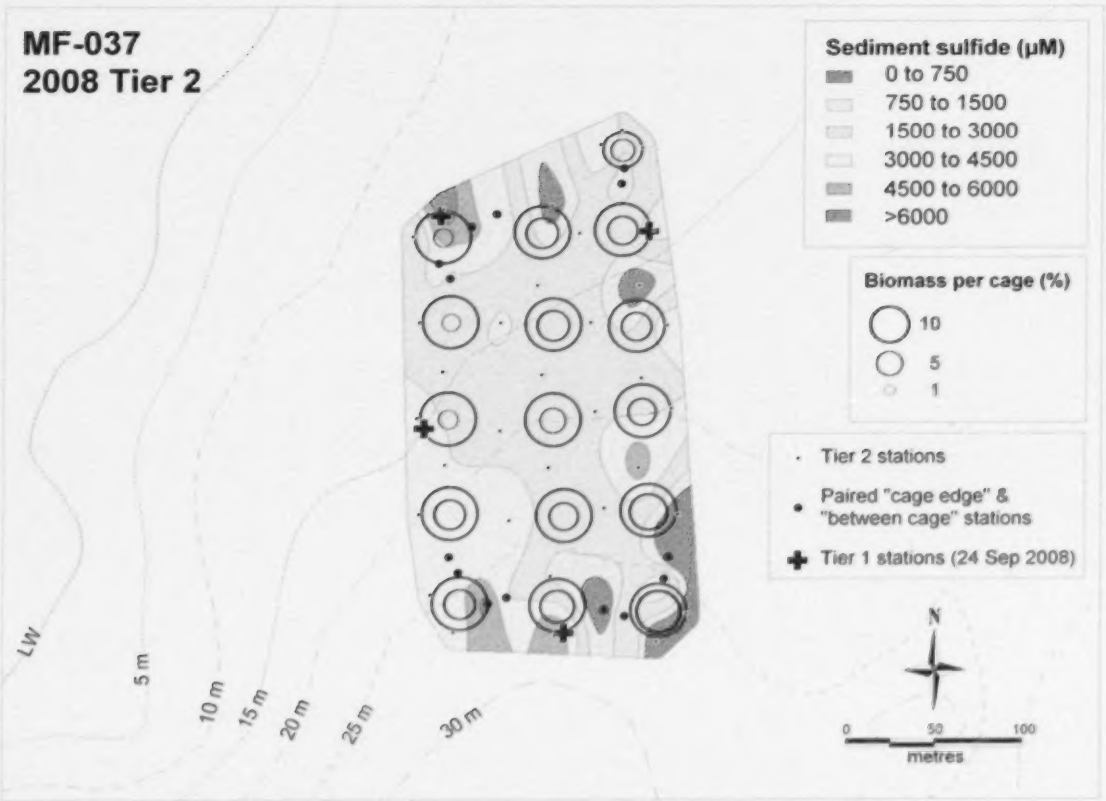

Fig. 10. Contour plot of sediment sulfide concentrations from Tier 2 monitoring at site MF-037 on 5-9 October 2008. Large circles indicate cage sizes and approximate locations (fifteen 100-m circumference cages, plus one 70-m cage). Smaller circles inside the cages represent the percent of the total biomass (592 700 kg) in each cage at the time of Tier 2 monitoring: the fish biomass was unevenly distributed among the 16 cages, with individual cages holding 2.6-12.3% of the total biomass. The average depth under the contoured area was approximately 18.8 m below chart datum (lowest normal tide).

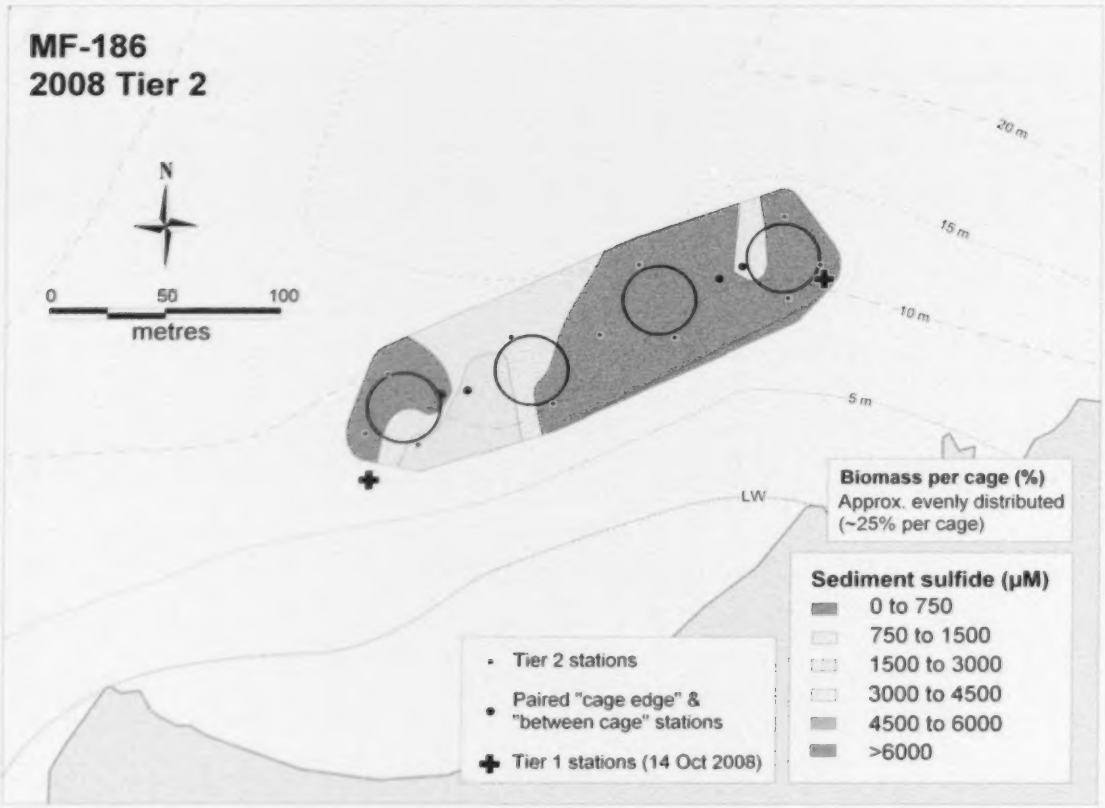

Fig. 11. Contour plot of sediment sulfide concentrations from Tier 2 monitoring at site MF-186 on 5 November 2008. Circles indicate cage sizes and approximate locations (four 100-m circumference cages). The Tier 1 monitoring report indicated that there were 140 000 fish on site (on 14 October 2008), with the biomass evenly distributed among the 4 cages (25% per cage; actual biomass data were not available). The average depth under the contoured area was approximately 14.0 m below chart datum (lowest normal tide).

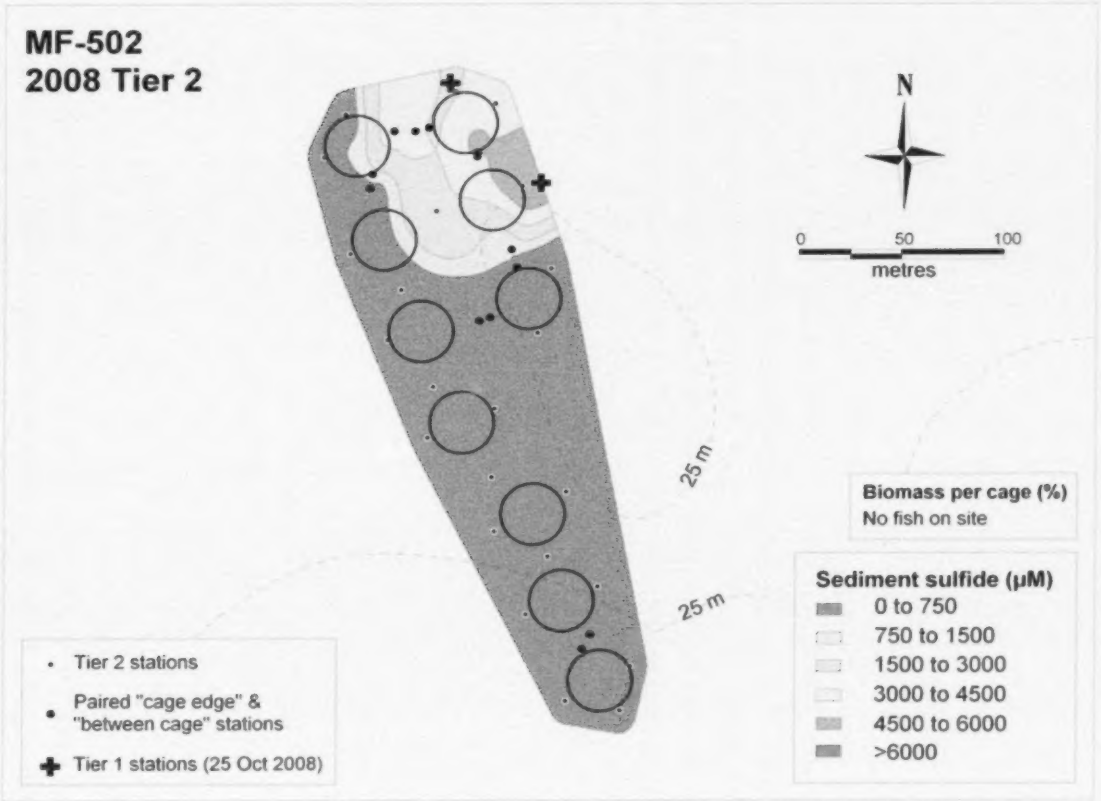

Fig. 12. Contour plot of sediment sulfide concentrations from Tier 2 monitoring at site MF-502 on 8-9 November 2008. Circles indicate cage sizes and approximate locations (ten 100-m circumference cages). There were no fish on site at the time of Tier 2 monitoring. The average depth under the contoured area was approximately 24.6 m below chart datum (lowest normal tide).

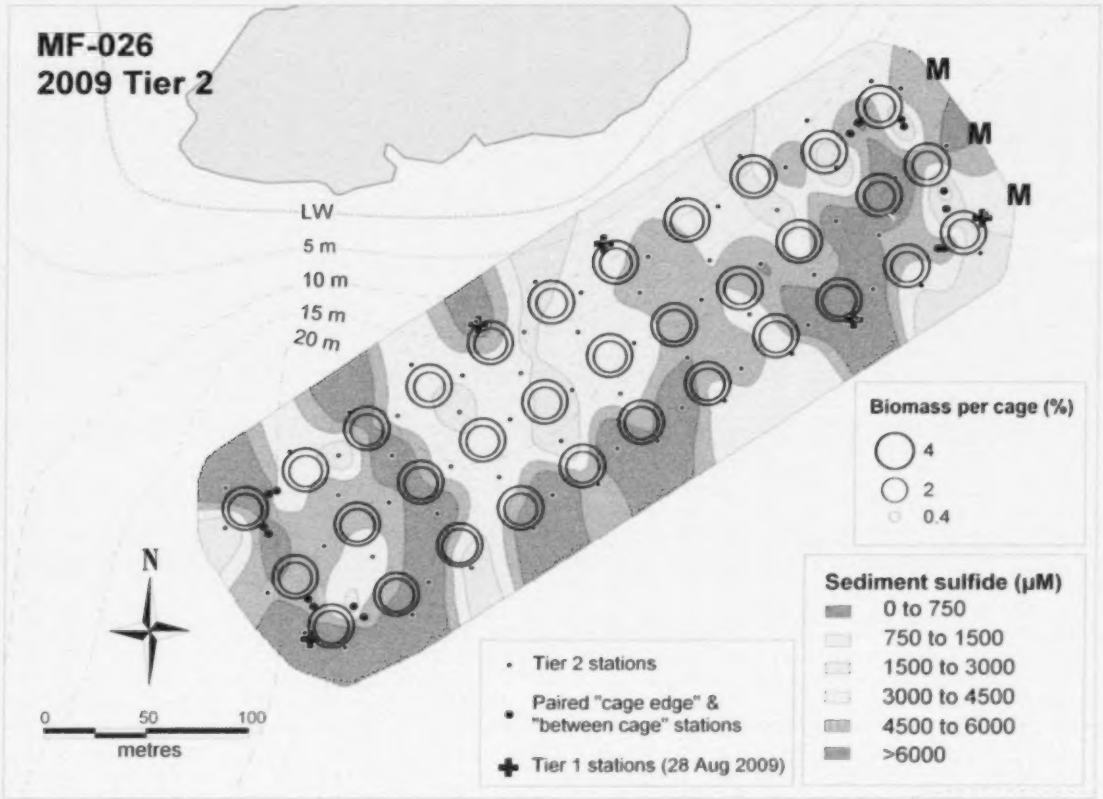

Fig. 13. Contour plot of sediment sulfide concentrations from Tier 2 monitoring at site MF-026 on 11-16 September 2009. Large circles indicate cage sizes and approximate locations (thirty-three 70-m circumference cages). Smaller circles inside the cages represent the percent of the total biomass (1 775 500 kg) in each cage at the time of Tier 2 monitoring: the fish biomass was relatively evenly distributed among the 33 cages, with each cage holding 2.5-3.6% of the total biomass. Tier 1 station locations are approximate, based on the aerial photo provided in the Tier 1 report (the coordinates provided in the Tier 1 report were incorrect). M = location of mussel cages. The average depth under the contoured area was approximately 20.9 m below chart datum (lowest normal tide).

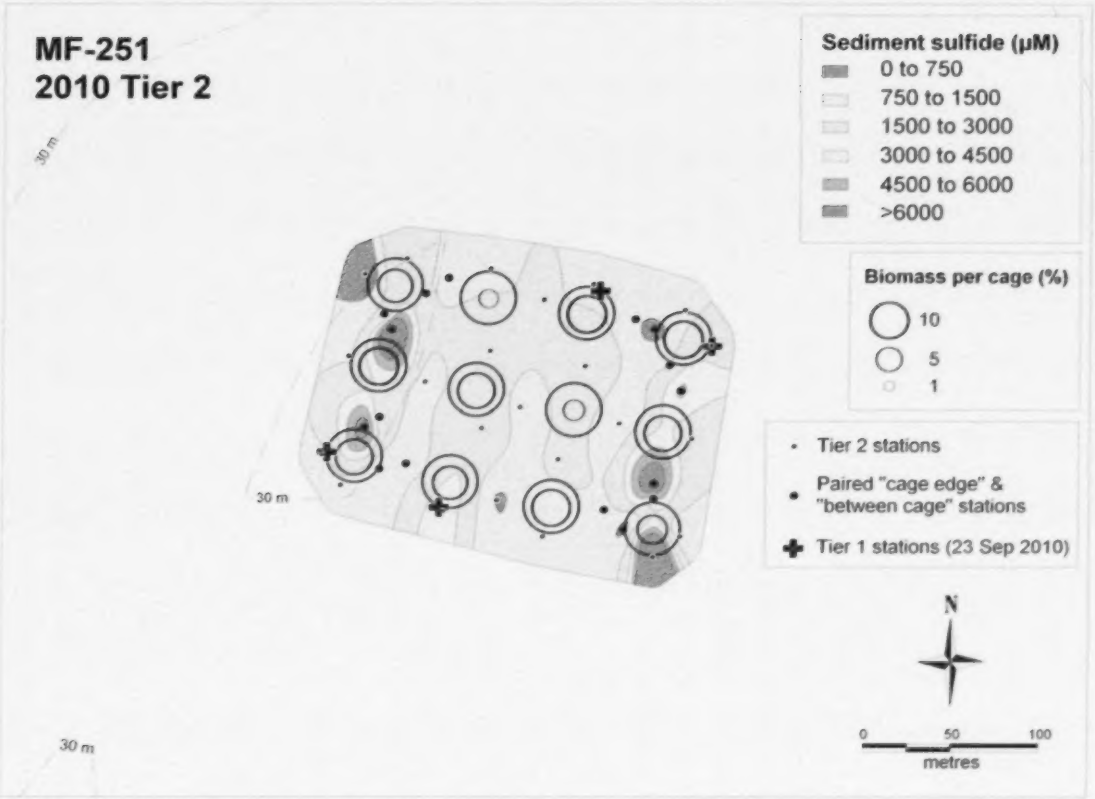

Fig. 14. Contour plot of sediment sulfide concentrations from Tier 2 monitoring at site MF-251 on 12 October 2010. Large circles indicate cage sizes and approximate locations (twelve 100-m circumference cages). Smaller circles inside the cages represent the percent of the total biomass (1 026 400 kg) in each cage at the time of Tier 2 monitoring: the fish biomass was unevenly distributed among the 16 cages, with individual cages holding 3.1-10.6% of the total biomass. The average depth under the contoured area was approximately 32.2 m below chart datum (lowest normal tide).

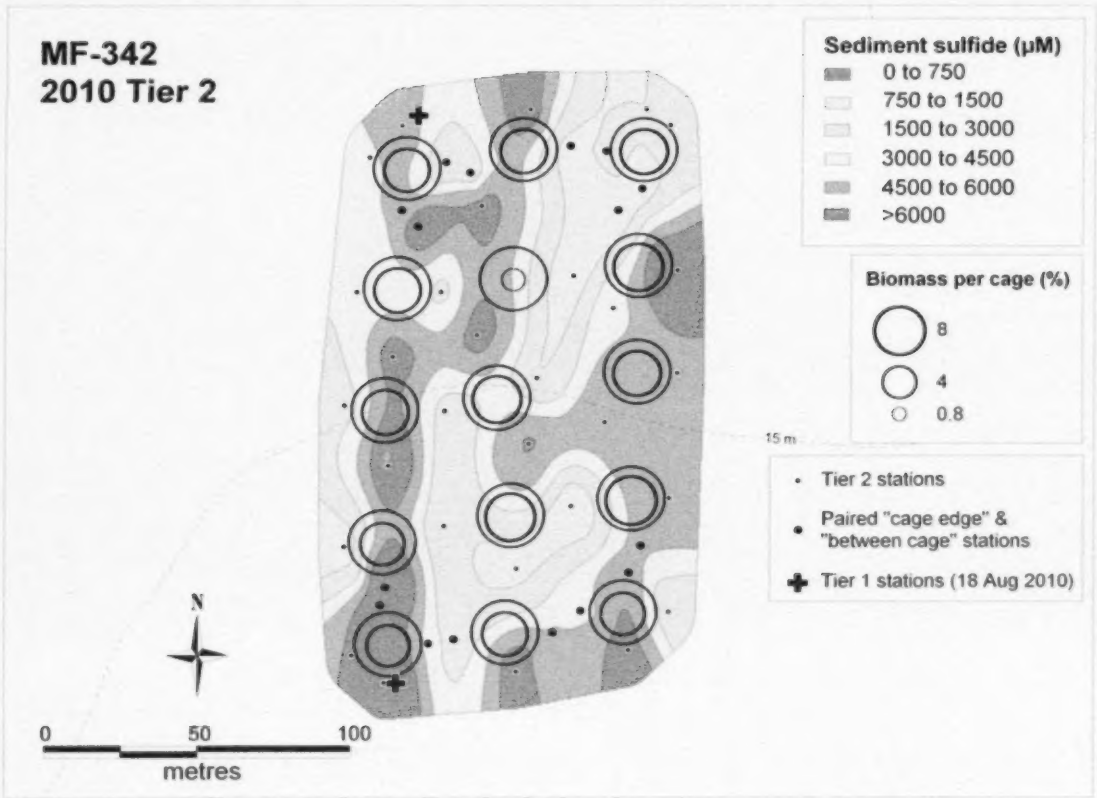

Fig. 15. Contour plot of sediment sulfide concentrations from Tier 2 monitoring at site MF-342 on 8 September 2010. Large circles indicate cage sizes and approximate locations (fifteen 70-m circumference cages). Smaller circles inside the cages represent the percent of the total biomass (463 700 kg) in each cage at the time of Tier 2 monitoring: the fish biomass was relatively evenly distributed among the cages, with the exception of the second cage from the north in the middle column, which held only 2.1% of the total biomass; each of the other 14 cages held 6.0-8.2% of the total biomass. The average depth under the contoured area was approximately 15.1 m below chart datum (lowest normal tide).

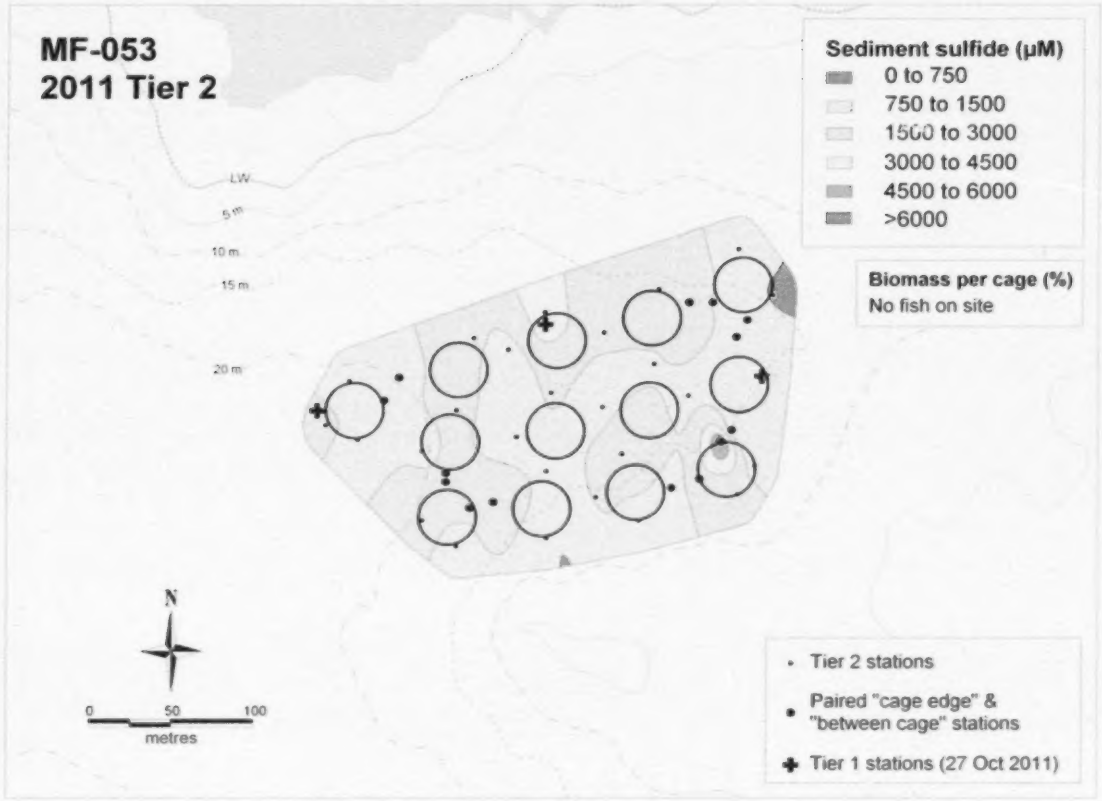

Fig. 16. Contour plot of sediment sulfide concentrations from Tier 2 monitoring at site MF-053 on 17 November 2011. Circles indicate cage sizes and approximate locations (thirteen 70-m circumference cages). There were no fish on site at the time of Tier 2 monitoring. The average depth under the contoured area was approximately 18.0 m below chart datum (lowest normal tide).

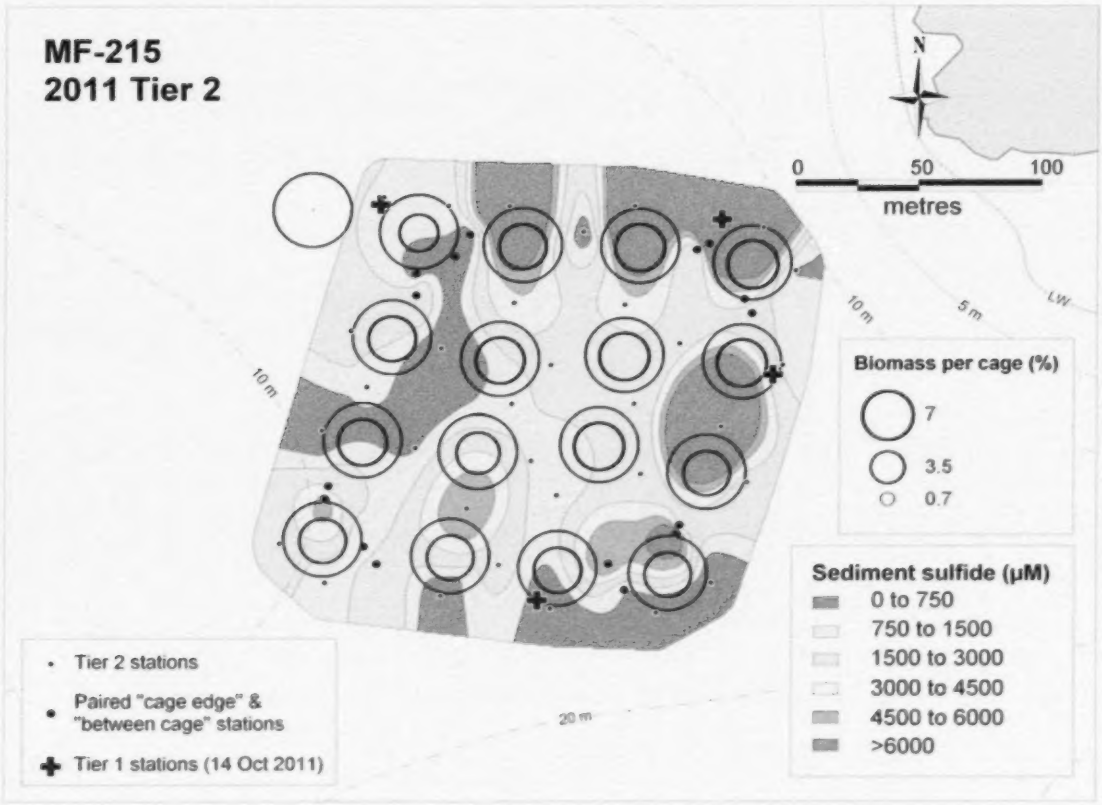

Fig. 17. Contour plot of sediment sulfide concentrations from Tier 2 monitoring at site MF-215 on 18 October 2011. Large circles indicate cage sizes and approximate locations (seventeen 100-m circumference cages). Smaller circles inside the cages represent the percent of the total biomass (1 892 600 kg) in each cage at the time of Tier 1 monitoring (14 October 2011): the fish biomass was relatively evenly distributed among 16 cages, ranging from 4.5-7.1% of the total biomass per cage (the cage at the northwestern corner was empty). Harvesting began on the day of the Tier 1 monitoring. The average depth under the contoured area was approximately 11.9 m below chart datum (lowest normal tide).

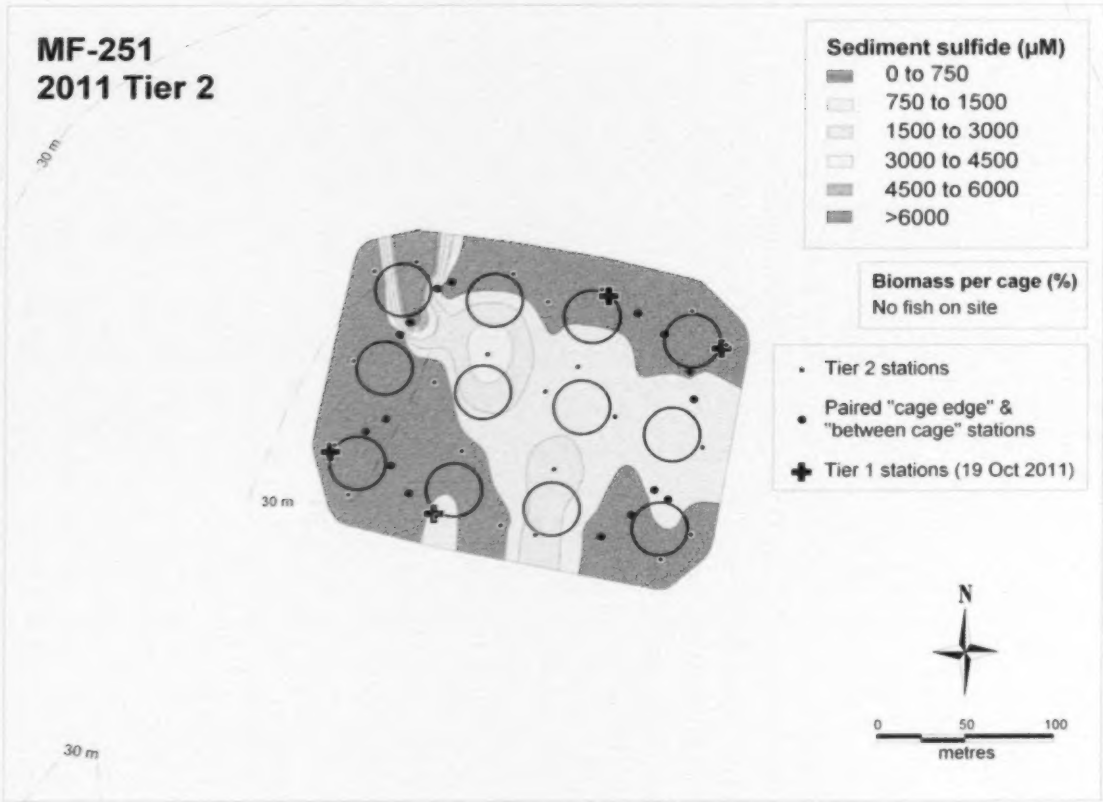

Fig. 18. Contour plot of sediment sulfide concentrations from Tier 2 monitoring at site MF-251 on 1 November 2011. Circles indicate cage sizes and approximate locations (twelve 100-m circumference cages). There were no fish on site at the time of Tier 2 monitoring. The average depth under the contoured area was approximately 32.2 m below chart datum (lowest normal tide).

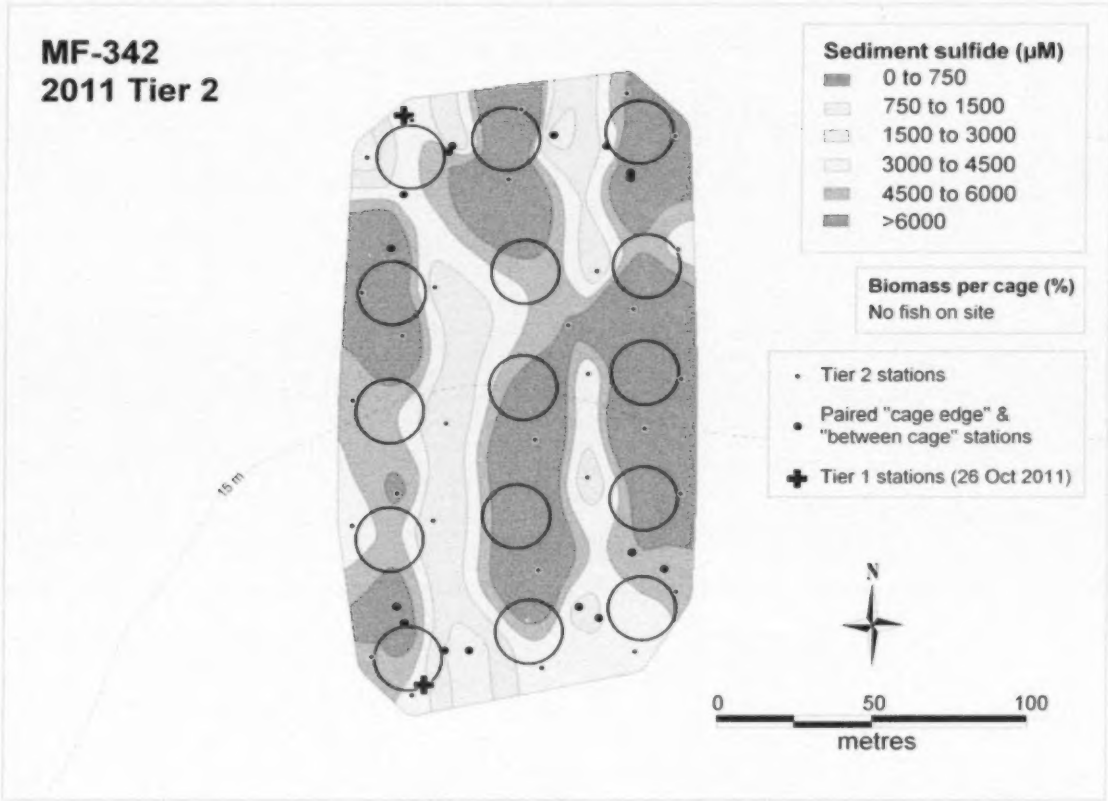

Fig. 19. Contour plot of sediment sulfide concentrations from Tier 2 monitoring at site MF-342 on 9 November 2011. Circles indicate cage sizes and approximate locations (fifteen 70-m circumference cages). There were no fish on site at the time of Tier 2 monitoring. The average depth under the contoured area was approximately 15.1 m below chart datum (lowest normal tide).

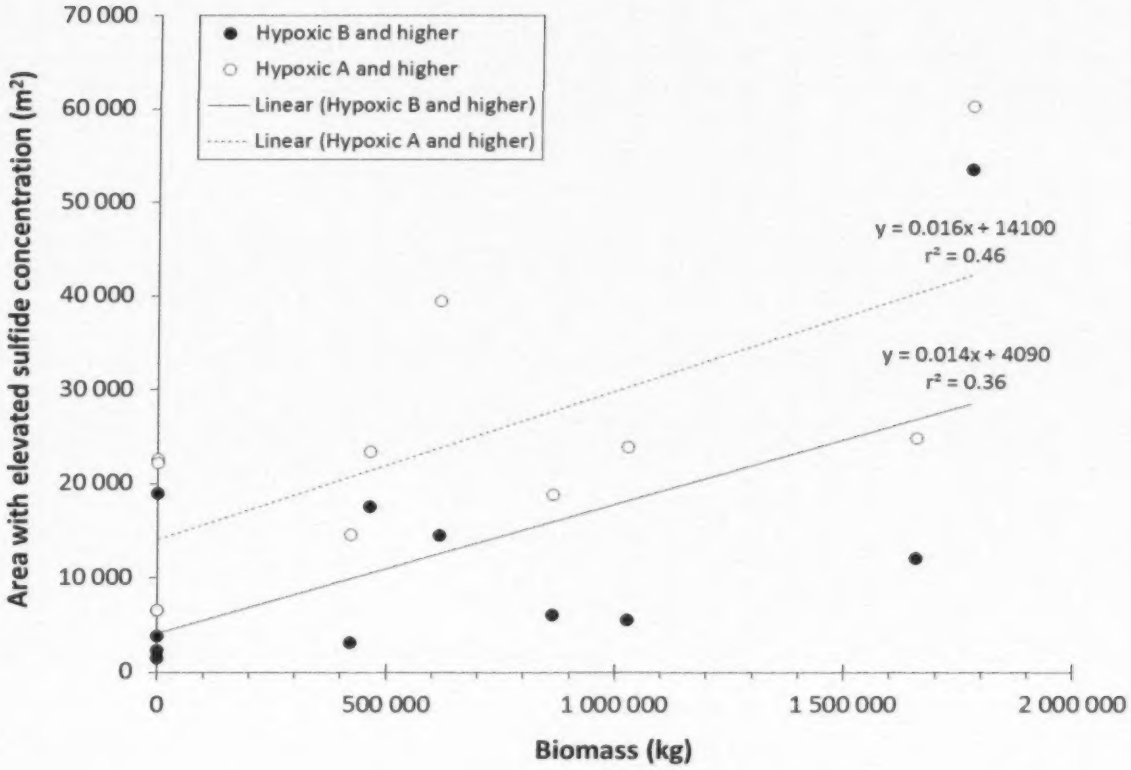

Fig. 20. Relationship between fish biomass and the contour area with elevated sediment sulfide concentrations in Tier 2 monitoring events at salmon farms in SWNB, 2007-2011. Elevated sulfide concentrations were defined as Hypoxic B or higher (>3000 μM S^{2-}) and Hypoxic A or higher (>1500 μM S^{2-}). Biomass data were available for 11 of the 14 Tier 2 monitoring events, and for 11 of the corresponding Tier 1 monitoring events (see Table 2).

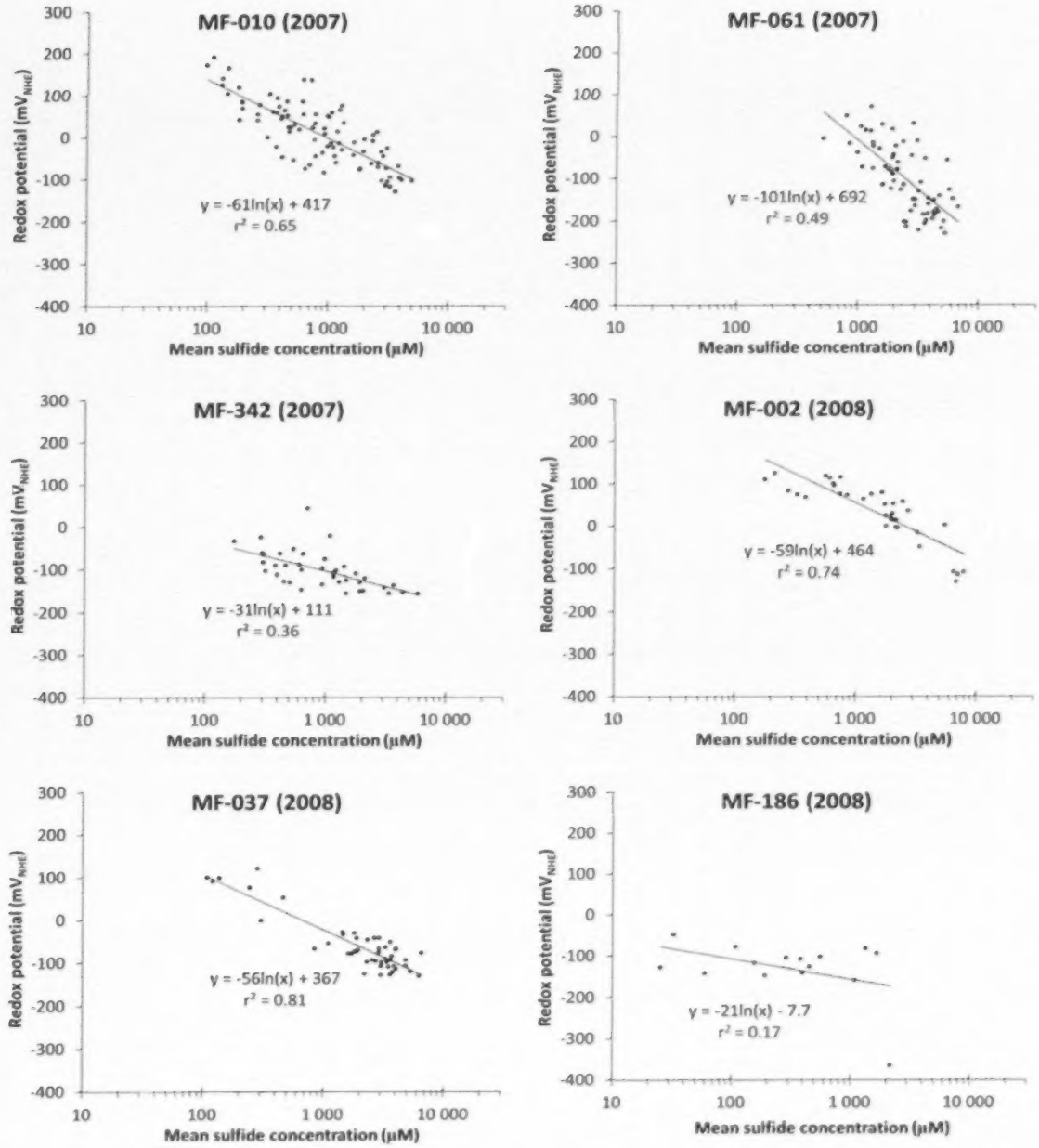

Fig. 21. Relationships between sediment sulfide concentration and oxidation-reduction (redox) potential in Tier 2 monitoring at SWNB salmon farms, 2007-2011. Tier 2 protocols require one redox and three sulfide measurements per monitoring station. The graphs show the mean sulfide concentration per station (log-transformed) vs. the redox value at each station. At the farms monitored in 2008, three redox measurements were made per station; in those cases, the mean redox values per station were used.

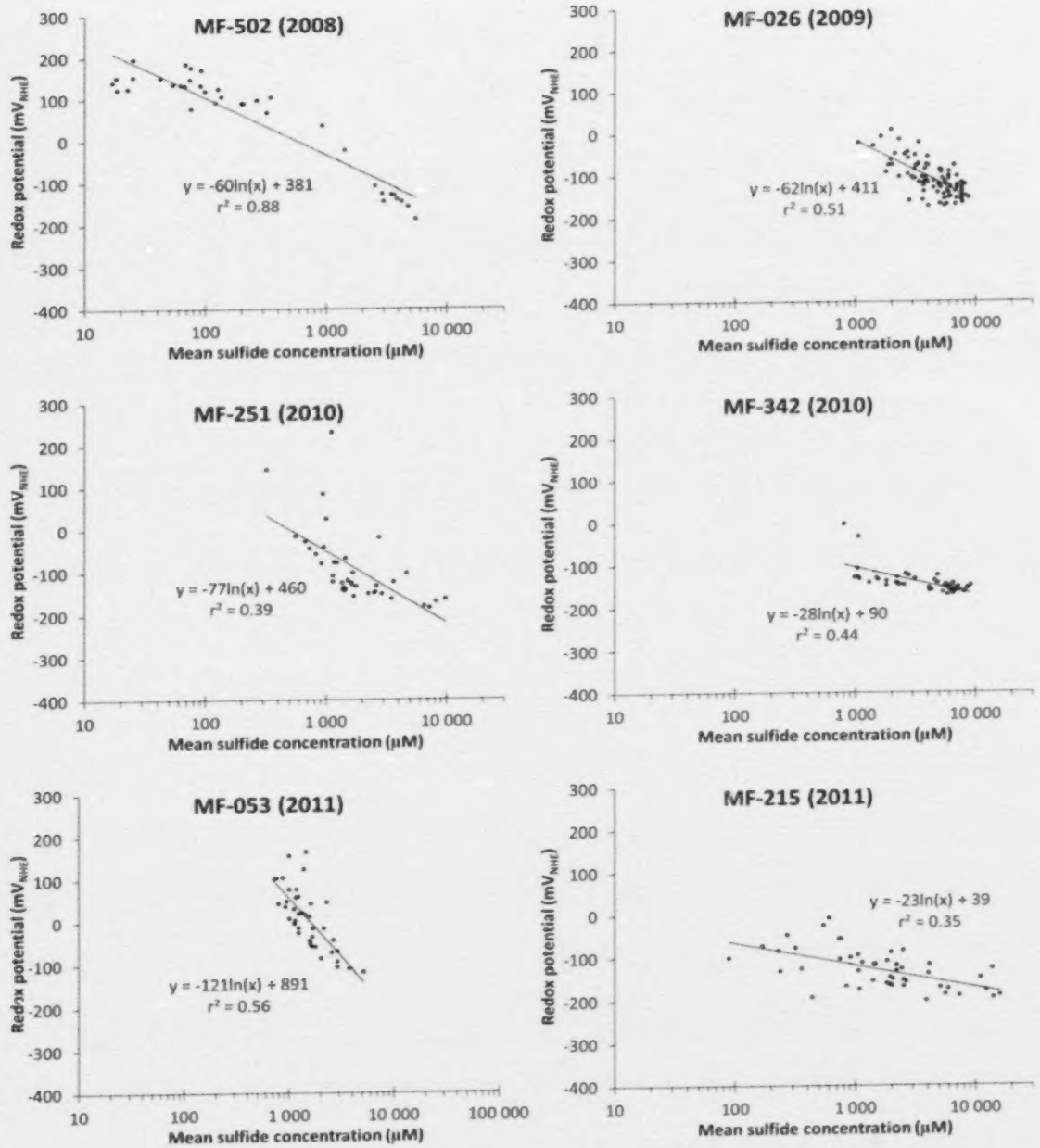

Fig. 21 (continued).

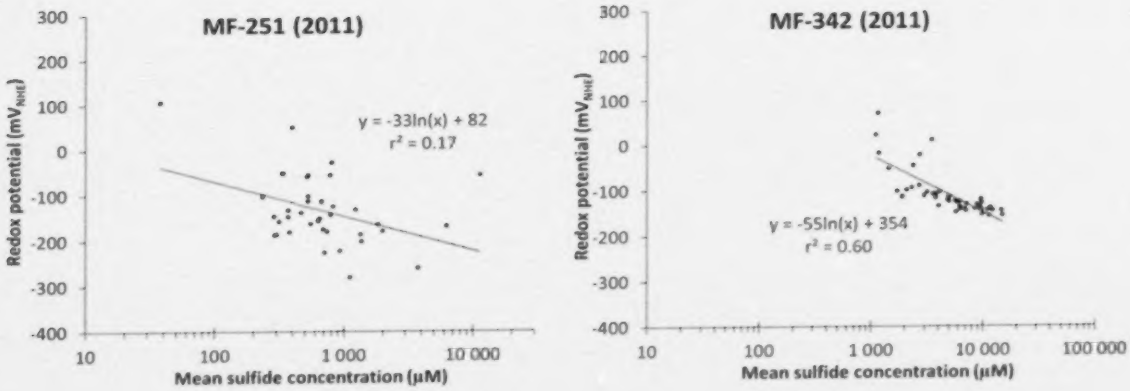

Fig. 21 (concluded).

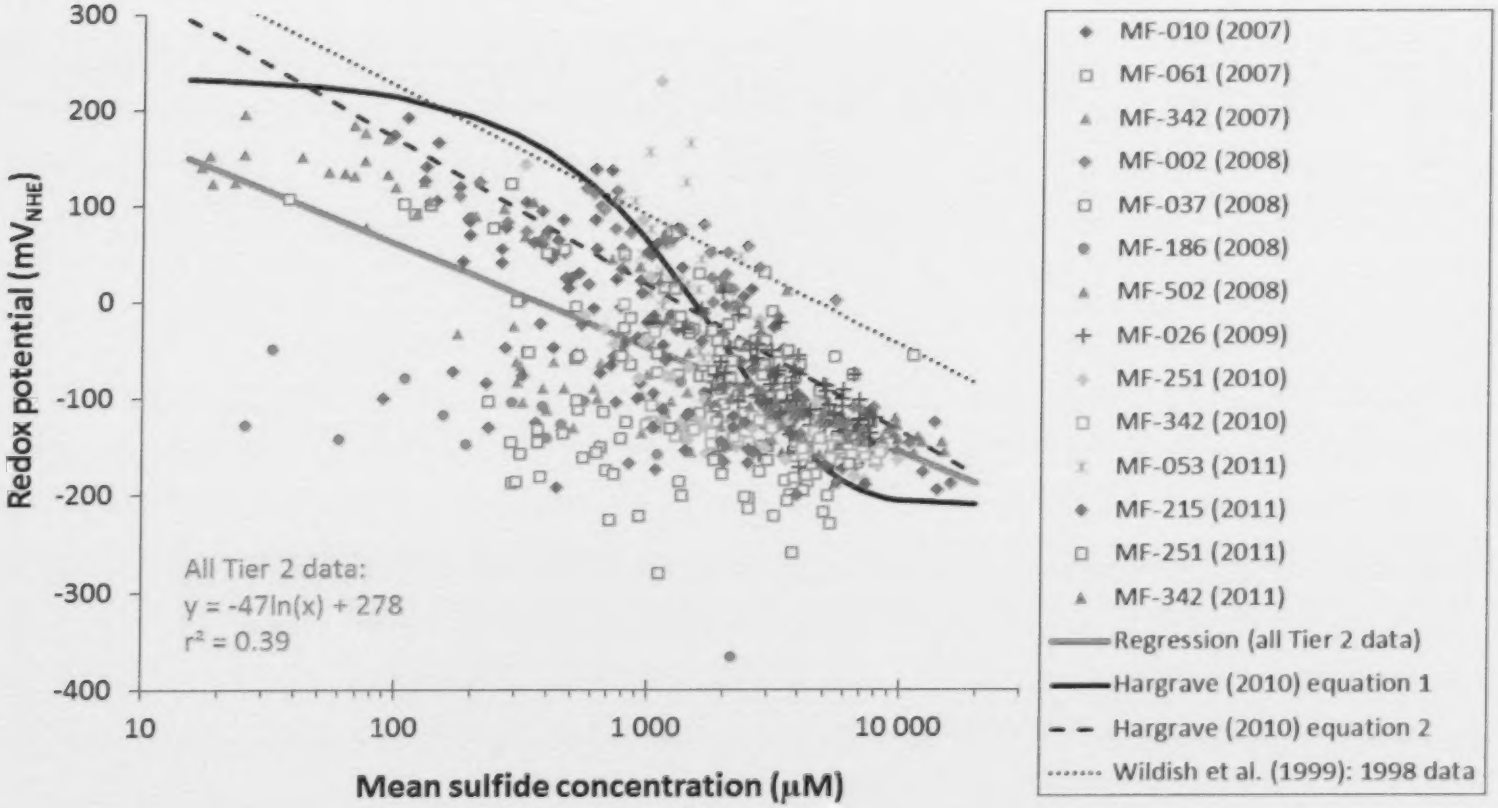

Fig. 22. The relationship between the sediment sulfide concentration (log-transformed) and the oxidation-reduction (redox) potential in all Tier 2 monitoring events at SWNB salmon farms, 2007-2011 (see caption to Fig. 21). Values shown are means of triplicate samples per monitoring station. The red line and equation is the linear regression for all Tier 2 monitoring data combined. Also shown are lines for relationships between sulfide concentration and redox potential from other studies at salmon farms in SWNB (see Table 12).